Volcanostratigraphy of Krakatoa Islands, South Lampung District, Lampung Province

Taufik Ismail1*, Mirzam Abdurrachman1,2, Yan Rizal1,2, and Kumala Hardjawidjaksana1

1 Department of Geology, Indonesia College of Mineral and Technology, Bandung 40263, Indonesia.
2 Department of Geology, Bandung Institute of Technology, Bandung 40132, Indonesia.

* Corresponding Author: taufikismail118@gmail.com (Taufik Ismail)

Abstract. The research area is within the territory of Nature Preserve and Marine Preserve region of Krakatoa Islands, South Lampung District, Lampung Province. The study aims to determine the surface geological, mapped on a scale of 1: 20,000, and to determine the geological history that forms the Krakatoa Islands. Volcanostratigraphy is made by combined from literature studied, shoreline analysis, petrographic analysis and field observation. From these results, it is poured into a map of geological outcrops, maps of volcanostratigraphy profiles, geological maps and geological sections. Volcanostratigraphy on the research area is divided into 30 rock units that consists of 22 lava, 8 pyroclastic and alluvial. Geological structure that developed in the research area in the form of secondary structure that is crater and caldera, and the primary structure that is sheeting joint, columnar joint, vesicular and autobreccia. New and detailed geological map of Krakatoa volcano is presented.

Keyword. Volcanostratigraphy; Sunda Strait; Krakatoa Islands; Indonesia.

1. Introduction
Krakatoa Islands is a Nature Preserve and Marine Preserve located in South Lampung District, Lampung Province which is more precisely in Sunda Strait, Indonesia (Figure 1). Krakatoa Islands consists of four islands namely is Sertung, Panjang, Rakata island and Anak Krakatoa island.

Last eruption of Krakatoa began in May 1883, and three days plinian eruption that occurred on 25, 26, August 27, 1883[1]. Eruption in 1883 included the largest eruption in the history of volcanic eruptions in the world with the power equivalent of 21,574 atomic bombs [2]. Anak Krakatoa Island is an active volcano that until now shows the volcanism activity. Anak Krakatoa volcano was born in 1927 and until now has erupted more than 80 times either explosive or effusive by about of 1 until 8 years, and eruptions can occur 1 - 6 times in one year [3]. High volcanic activity has been triggered by partial melting on the subduction of Hindia plate which thinning as a result of mantle plume activity beneath Krakatoa volcano [4].
Volcanostratigraphy in this research area is intended to arrange rocks or volcanic deposit based on the sequence of volcanic events and evolution of volcanic formation can be understandable. Geological research and mapping related to the stratigraphy of Krakatoa island was conducted in 1883 by [5] and in 1997 by [3] and we has been used as a reference in the made volcanostratigraphy of Krakatoa islands.

![Figure 1](image_url). Location map of Krakatoa islands. Red triangle location of Anak Krakatoa Volcano.

2. Data and Method
Principle of vulcanostratigraphy, basically rock units or volcanic deposits are defined as unity of rocks or volcanic deposits as a result of volcanic activity, both primary and secondary in one-time interval. This principle basically not only divides the rock characteristics, but also divides by source eruption, eruption cycle, and occurrence time of eruption. The source of eruption can be a crater or caldera. Lithology with the same characteristics can be distinguished if the source and time is different [6].

Rocks unit in research area that has been grouped and named which refers to the code of Indonesian stratigraphic by [6]. Pyroclastic deposition mechanism has been grouped which refers to [7, 8] and pyroclastic texture which refers to [8, 9]. Igneous rock has been named on the basis of the igneous rock classification by [10].

In this study, we have observed directly in the field with geological mapping method and collected 142 outcrop site (Figure 2). Therefore, we took samples in Anak Krakatoa island for petrography analysis (Table 1) or for other analysis which can support for further research. Other than that, we collected some literature to be studied and made as a reference. In addition to sampling, we have created stratigraphic profiles in some places that we think are perfect for we creat the stratigraphic profile and we have been shown in map of volcanostratigraphic profile (Figure 3).
Figure 2. Outcrop site distribution map of Krakatoa islands. Explanation of colors in the map for dark red is basaltic lava, red is andesitic lava, brown is laharic deposit, green is pyroclastic flow and yellow is pyroclastic fall and surge within different symbols.

Table 1. Sample petrographic analysis each rock unit with sample code. For sample location, see figure 2.

| No | Island | Rock Unit | Sample Code |
|----|--------|-----------|-------------|
| 1  | A      | Akl1      | St75        |
| 2  | A      | Akl2      | St46        |
| 3  | N      | Akl3      | St38        |
| 4  | A      | Akl4      | St81        |
| 5  | A      | Akl5      | St78        |
| 6  | A      | Akl6      | St32        |
| 7  | K      | Akl7      | St37        |
| 8  | K      | Akl8      | St40        |
| 9  | A      | Akl9      | St7         |
| 10 | A      | Akl10     | St62        |
| 11 | A      | Akl11     | St20        |
| 12 | A      | Akl12     | St28        |
| 13 | A      | Akl13     | St49        |
| 14 | A      | Akl14     | St77        |
| 15 | A      | Akl15     | St16        |
| 16 | A      | Akl16     | St43        |
| 17 | A      | Akl17     | St28        |
Figure 3. Volcanostratigraphic profile map of Krakatoa islands. See Figure 2 for explanation of colors. In the map, there are photos and sketches for make reading easier with explanation of outcrop located below the photo, the direction of arrow is to see where the outcrop on the geological map in the center volcanostratigraphic profile map, height of the outcrop already exists beside the sketche and located of litologic symbol inside sketche.

We also conducted an indirect observation through landsat imagery of google earth and the shoreline digitization from 1984 to 2017 in the research area. This sight is very helpful for us in determining rock units and relative age even creating the geological map of Krakatoa islands, especially for geological of Anak Krakatoa island. Result of the shoreline digitization which collected from 1984 to 2017, we presented to the shoreline map of Krakatoa island (Figure 4). To determine the volcanostratigraphy in the research area, the first to do is to see topography widely to predict the direction of eruptive products and sources of eruption.
3. Result and Discussion

Predominant of rock that formed Krakatoa islands came from volcano activity especially lava and pyroclastic deposit. Based on observations in the field contained within outcrop site distribution map, volcanostratigraphic profile map and supported by petrography analysis, shoreline which included to shoreline map and study of literature, generally the research area can be divided into three Khuluk namely is, Khuluk of Old Krakatoa, Khuluk of young Krakatoa and Khuluk of Anak Krakatoa. Khuluk of Old Krakatoa and Khuluk of Young Krakatoa this is not clearly visible eruption center because it is part of catastrophic eruption that removes some parts of the body of volcano and also very intensive erosion. Different from Khuluk Anak Krakatoa which volcanic cones are still visible.

Khuluk of Old Krakatoa (Figure 5) divided into 4 rock unit that consist of lava 1 of Old Krakatoa (Ktl1), pyroclastic fall of Old Krakatoa (Ktpj), lava 2 of Old Krakatoa (Ktl2), and pyroclastic flow of Old Krakatoa (Ktap). Lava 1 of Old Krakatoa rock unit (Ktl1); generally, outcrops in this rock unit are bright gray. In some places appear brownish red at the bottom and top of this rock unit, there is sheeting joint and autobreccia. Lithology of this rock unit is dominated with andesitic lava flow. Pyroclatic fall of Old Krakatoa rock unit (Ktpj); direct contact with previous rock unit below with irregular rock contact. Composition of this rock unit is pyroclastic fall deposit with layers consists of a pumice, scoria,
lapilli and dust deposit. Lava 2 of Old Krakatoa rock unit (Ktl2); outcrops on this rock unit is gray in the middle of outcrop and brownish red at the top outcrop, lithology of this rock unit is andesitic lava flow, position of this unit is above the units below is pyroclatic fall of Old Krakatoa rock unit (Ktjp) with indirect contact. Pyroclastic flow of Old Kraklaktoa rock unit (Ktap); rock units in the form of pyroclastic flows was composed of dominantly pumice and scorea on several outcrops, this unit is the last of old Krakatoa's volcano product and the first caldera formed around 416 AD [1,3,5,7,11,12].

![Figure 5](image)

**Figure 5.** Outcrop from each rock units in the research area belong Khuluk of Old Krakatoa.

Khuluk of Young Krakatoa devided into 3 Gumuk that consist of Gumuk of Rakata, Gumuk of Danan and Gumuk of Parbuwatan. Gumuk of Rakata (Figure 6) consist of several rock units from old to young is pyroclastic fall 1 of Rakata (Rkjp1), basaltic lava of Rakata (Rklb), pyroclastic fall 2 of Rakata (Rkjp2) and basaltic-andesitic dike of Rakata (Rkrab). Pyroclastic fall 1 (Rkjp1); dominantly was composed of pyroclastic fall with minor pyroclastic flow deposit, has a brownish gray color, consisting of ash, scoreous lapile until the bomb, there is andesitic lava as result effusive activities. Basaltic lava of Rakata (Rklb); this rock unit was composed with basaltic lava dominantly with minor fall deposit, total thickness is estimated from 350 until 450 meters [5]. Pyroclastic fall 2 of Rakata (Rkjp2); This unit is on the peak of Rakata island and can not be seen directly because the field is so dangerous to reach and requires special equipment. According to [5], this unit was composed of pyroclastic fall deposit, grained scoreous lapilli until the bomb, brick red to brown colored. Basaltic-andesitic dike of Rakata (Rkrab); well exposed in the north wall of Rakata island, dikes that the average thickness of about 2 until 6 meter. Andesitic dike along with growth Danan and Parbuwatan Volcano. Basaltic dike is estimated as a result of the final period of Rakata volcano [5].
Figure 6. Outcrop from each rock units in the research area belong Gumuk of Rakata.

Gumuk of Danan is a volcano before 1883 eruption, the rest is andesitic lava, exposed between Anak Krakatoa island and Panjang island, outcrop has a high around 3 meters above sea level (Figure 7). Gumuk of Parbuwatan has not found outcrop from the Parbuwatan volcano activity.

Figure 7. Outcrop from Gumuk of Danan as a rest from Danan volcano activity.

Pyroclastic flow of Khuluk’s Young Krakatoa is a result of cataclysmic eruption of 1883 AD, main deposit is pyroclastic flow deposit with minor surge and fall deposit, was composed of pumice dominantly, grained lapilli until the bomb (Figure 8).
Khuluk of Anak Krakatau is a volcano that was born in 1927 AD [1,3,5,11-13] (Figure 9). Khuluk of Anak Krakatau devided into 2 Gumuk that consist of Gumuk of east Anak Krakatoa and Gumuk of west Anak Krakatoa. Gumuk of east Anak Krakatoa that formed by dominated pyroclastic deposits of the 1927 AD until 1960 AD. Gumuk of west Anak Krakatoa that formed by 17 lava flows was composed of andesite and basalt (Figure 10) and pyroclastic deposit with dominated by pyroclastic fall deposit (Figure 11). Rock units from each Khuluk of Anak Krakatoa was separated by petrography analysis, landsat imagery analysis and geological mapping. Provision of age for each rock units located in the research area was obtained using shoreline analysis and reference.

**Figure 8.** Outcrop from Pyroclastic flow of Khuluk’s Young Krakatoa as a result 1883 eruption.

**Figure 9.** Anak Krakatoa volcano.
Figure 10. Lava from each rock units. These pict has taken at Anak Krakatoa island as result effusive erupted of Anak Krakatoa volcano.

Figure 11. Pyroclastic deposit from Anak Krakatoa volcano as result explosive erupted of Anak Krakatoa volcano.

The geological structure that develops in the research area is divided into 2 structures consist of primary geological structure and secondary geological structure. Primary geological structure of rocks is a structure that shows how the process of rock formation is due to the primary geological structure formed together with the formation of rocks. Secondary geological structure of rocks is a structure that shows how the process of geologic structures evolved that is reflected in the rocks. Secondary geological structures are structures formed after they are formed.

Primary geological structure has availabled in this study area (Figure 12) generally formed vesicle on every lava flow of Anak Krakatoa volcano, autobrecia is existed, there are columnar joint and sheeting joint on andesitic lava of old Krakatoa (KtI2), accretionary lapili on the bottom of the pyroclastic unit of Anak Krakatoa.
Secondary geological structures in the research area are generally controlled by volcanic activity. Secondary geological structures in the research area consist of crater and caldera. Structure of the crater in the research area there are 2 crater structures consisting of crater structure of east Anak Krakatoa and crater structure of west Anak Krakatoa. Crater structure of west Anak Krakatoa is the remains of Anak Krakatoa crater from 1927 to 1960 and already not available volcanic activity (Figure 13). Crater structure of west Anak Krakatoa is at the peak of Anak Krakatoa volcano today and still shows volcanic activity (Figure 14).

Figure 12. Primary geological structure.

Figure 13. Crater structure of west Anak Krakatoa. Crater structure is at the first peak of Anak Krakatoa volcano with a height of about 150 meters above sea level.
Figure 14. Crater structure of east Anak Krakatoa east. This crater structure is located at the top of gununapi Anak Krakatoa with a height of about 320 meters above sea level. This picture is obtained from BKSDA Lampung documentation.

Caldera structure of the study area is indicated by a very steep slope (Figure 15), on topographic maps displayed with very tight contours. This cliff is in several places that is east cliff of Sertung island, north wall of Rakata island and west cliff of Panjang island. The cliff is indicated as a caldera with a diameter of more than 4 kilometers.

Figure 15. Cliff in the research area as evidence of existence caldera structure.

This caldera structure is evidence of a big eruption of old Krakatoa volcano in 416 AD [1,3,5,11-13], and young Krakatoa volcano in 1883 AD [1-3,5,11-14]. This caldera structure is very clearly on the subsurface that the depression with a depth of 200 to 250 below sea level [15] (Figure 16).
From the aspect of field observation, shoreline analysis and supported by petrography analysis in distinguished rock units located in Anak Krakatoa Island and Krakatao Islands rock units, on that based we have summarized and poured to the geological map of Krakatoa islands (Figure 17), volcanostratigraphy of Krakatoa islands (Figure 18) and geological section of Krakatoa islands (Figure 19).

Figure 16. Caldera structure of Krakatoa islands [15].

Figure 17. Geological map of Krakatoa island. See figure 18, for explanation of colors.
Figure 18. Volcanostratigraphy of Krakatoa islands.

Figure 19. Geological section of Krakatoa islands. See figure 17 for direction of line section.
From these results, we tried to make an illustration of geological history in the Krakatoa islands and [3,5,11-13] as our reference. We divided the geological history of the Krakatoa islands into 5 phases that is development phase of old Krakatoa volcano, destruction phase of old Krakatoa volcano, development phase of young Krakatoa volcano, destruction phase of young Krakatoa volcano, and development phase of young Krakatoa volcano.

These development phase of young Krakatoa volcano has begun before 416 AD. This phase is the beginning of development Krakatoa volcano before 416 AD. In this early phase Krakatoa Tua produces andesite lava flow (Ktl1) (Figure 20). Furthermore, this unit is overlaid by pyroclastic deposit (Ktjp) with fragments of pumis and generally this unit is coloured red (Figure 21). Furthermore, the effusive eruption of Krakatoa volcano is indicated by andesit lava flows (Ktl2) with sheeting joint, columnar joint and autobreccia (Figure 22). Field appearance on this unit shows the tip of the lava flow of this unit.

**Figure 20.** Block of geological history of the Krakatoa that formed of lava 1 of old Krakatoa (Ktl1).

**Figure 21.** Block of geological history of the Krakatoa that formed of lava 1 of old Krakatoa (Ktl1).
Figure 22. Block of geological history of the Krakatoa that formed of pyroclastic fall old Krakatoa (Ktjp).

The next phase is the destruction phase of old Krakatoa volcano in 416 AD [11-13], shown by flow pyroclastic product (Ktap) (Figure 23). After Krakatoa Tua volcano erupts with catastrophic eruption and then the occurrence of collapse which removes some parts of the body of Krakatoa Old volcano (Figure 24), and is divided into three islands that is Panjang island, Sertung island and Rakata island (Figure 25).

Figure 23. Block of geological history of the Krakatoa that formed of pyroclastic flow of old Krakatoa (Ktjp).
The next phase is the development phase of young Krakatoa volcano in 1200 AD. The young Krakatoa volcano produces three volcanoes, consisting of Rakata volcano, Danan volcano and Parbuwatan volcano [11-13]. Rakata volcano produces 4 rock units, consisting of pyroclastic fall of young Krakatoa (Rkjp1) (Figure 26), overlaid by the basaltic lava flow of young Krakatoa (Rklb) which simultaneously with growth of Danan volcano with unknown products (Figure 27), the basalt lava flows are overlaid by pyroclastic fall of young Krakatoa (Rkjp2) which simultaneously with growth of Parbuwatan volcano [11] (Figure 28). Danan volcanic products that can be known form bootsman rots [11]. The product is formed along with dikes that is in the north cliff of the Rakata island. According to [11], this product is the last stage of the development phase of young Krakatoa volcano (Figure 29).
Figure 26. Block of geological history of the Krakatoa that formed of pyroclastic fall 1 of young Krakatoa (Rkjp1).

Figure 27. Block of geological history of the Krakatoa that formed of basaltic lava of young Krakatoa (Rklb).

Figure 28. Block of geological history of the Krakatoa that formed of pyroclastic fall of young Krakatoa (Rkjp2).
The last stage of the development phase of young Krakatoa volcano.

This phase is the destruction phase of young Krakatoa volcano on the date 25 – 27 August 1883, started with the roar of the plinian eruption [1, 12]. According to [1, 16] this eruption was ejected 18 km$^3$ pyroclastic with high around 80 km (Figure 30). At the same time collapse occurs in the body of the volcano due to emptied in the magma chamber that has been issued (Figure 31). According to [13], that the tsunami occurred after the eruption due to the collapse of the volcano body that threw seawater above it. After the eruption is then deposition product of pyroclastic flow, pyroclastic fall and pyroclastic surge of young Krakatoa, which covers more than 75% of the each area in the Krakatoa islands (Figure 32).

![Figure 29. The last stage of the development phase of young Krakatoa volcano.](image)

**Figure 29.** The last stage of the development phase of young Krakatoa volcano.

![Figure 30. Block of geological history of the young Krakatoa that shown of ultraplinian eruption in 1883 AD.](image)

**Figure 30.** Block of geological history of the young Krakatoa that shown of ultraplinian eruption in 1883 AD.
Figure 31. Block of geological history of the young Krakatoa that formed second caldera structure.

Figure 32. Block of Krakatoa islands is divided into three islands consist of Panjang island, Sertung island and Rakata island after 1883 AD erupt.

This phase is development phase of Anak Krakatoa volcano that begins with an underwater eruption that ejects volcanic ash up to sea level with a height reached 40 m in 1927 AD (Figure 33) [3]. The first products produced by Anak Krakatoa volcano are pyroclastic deposits in the form of pyroclastic fall, flow pyroclastic, pyroclastic surge and lahar. In this case, we incorporated them in pyroclastic of east Anak Krakatoa (Aktp). The crater from the eruption center of the Anak Krakatoa volcano is indicated by a crater opens to the southwest (Figure 34). In 1972 AD, the eruption center moved to the northwest with products dominated by lava flow. Anak Krakatoa Volcano has produced 17 lava flow products (Aktl), with pyroclastic which is dominated by pyroclastic fallout (Akbp), see figure 17-18. Anak Krakatoa volcano is included in the volcano that still active until now. Krakatoa islands now have 4 islands with morphology as a resulted from volcanic activity (Figure 35).
Figure 33. Block of Krakatoa islands that has shown an underwater eruption in 1927 AD.

Figure 34. Block of geological history of the Krakatoa islands that formed of pyroclastic of Anak Krakatoa volcano (Aktp) 1927 until 1960 AD.

Figure 35. Block of geological history of the Krakatoa islands that shown Anak Krakatoa volcano with altitude 320 meter and stil grew up until present day.
4. Conclusions

- Volcanostratigraphy of Krakatoa island is part of Sunda arc extended the northern of Sumatra island to the eastern of Java island. The Krakatoa Islands has a history of two caldera development, the first caldera formed in 416 AD and in 1883 AD. Volcanostratigraphy of Krakatoa islands is devided into 3 Khuluk that is Khuluk of old Krakatoa, Khuluk of young Krakatoa dan Khuluk of Anak Krakatoa, and at least there is 29 rock units in Krakatoa islands. In vulkanstratigrafi case, this Anak Krakatoa volcano need more detailed research related age from pyroclastic deposit of Anak Krakatoa volcano. On vulcanostratigraphy, this Krakatoa island especially on this Anak Krakatoa volcano will continue to change, consider to very intense of the activity of Anak Krakatau volcano and need for research at least 1 time in five years to see the development of Anak Krakatoa volcano geologically and vulcanostratigraphy.

- Anak Krakatoa volcano is still going to grow up with the time that can not be predicted when will happen big eruption again. Seeing from the growth side of Anak Krakatau volcano that was born in 1927 AD and in 2018 it has reached a height of approximately 320 meters, then Anak Krakatoa volcano needs time more or less 190 years to reach the heights 1000 meters same as altitude of old Krakatoa volcano and young Krakatoa volcano.

Acknowledgements

We are very thankful to the head and staff of SKW III BKSDA Lampung, Lampung Province, Sumatra for their permission, assistance and help during our field work.

References

[1] van Verbeek, R.D.M., 1885. The time determination of the biggest explosion of Krakatoa on August 28, 1883, Science 3, 1884, Pg.43-55, and Arch. Neerl. Haarlem 20, 1885, pp.1-13.
[2] De Neve, G.A., 1981. Historical notes on Krakatoa’s eruption of 1883, and activities in previous times, National Institute Oceanology, Pub. No.III-14, Pg.45.
[3] Sutawidjaya, I., 2006. Pertumbuhan Gunung Api Anak Krakatoa setelah letusan katastrofis 1883, Indonesia Journal of Geology, Vol.1 No.3, pp.143-153.
[4] Abdurrahman, M., Widiyantoro, S., Priadi, B., & Ismail, T. Geochemistry and Structure of Krakatoa Volcano in the Sunda Strait, Indonesia. Geosciences 2018, 8, 111.
[5] Effendi, A.C., Sukhyar, R., & Bronto, S., 1983, Geology of Krakatoa Complex, Symposium100 years Krakatoa 1883 – 1983, VSI, pp.1-7.
[6] Martodjojo, S. and Djuhaeni. 1996, Sandi Stratigrafi Indonesia, Komisi Sandi Stratigrafi Indonesia, Ikatan Ahli Geologi Indonesia, Jakarta.
[7] McPhie, J., Doyle, M., & Allen, R, 1993, Volcanic Textures: A Guide to the Interpretation of Textures in Volcanic Rocks, University of Tasmania, Tasmania, pg.197.
[8] Yuwono, Y.S., 2004, Pemetaan Daerah Vulkanik, Panduan untuk Pemetaan Lapangan, Laboratorium Petrologi dan Geologi Ekonomi, ITB, Bandung.
[9] Fisher, R.V., dan Schminke, H.U., 1984, Pyroclastic, Springer Verlag, pg.472.
[10] Le Bas, M.J. and Streckeisen, A.L. 1991. The IUGS Systematics of Igneous Rocks, Journal of the Geological Society, London. 148. pp.825- 833.
[11] Bronto, S., 2000, Volcanic Hazard Assessment of Krakatoa Volcano, Sunda Strait, Indonesia, Jurnal Geologi Tata Lingkungan, Vol. 12 No. 1, hal. 20-29, Bandung.
[12] Stehn, Ch. E., 1929, The geology and volcanism of the Krakatoa Group. Part I, 1-55 plates, In 44th Pac. Sci. Congr. Batavia, Guidebook, pg.118.
[13] Winchester, S., 2003, Krakatoa, The Days The World Exploded, August 27th, 1883, Penguin Books. Ltd., London, ISBN: 978-0-14-192623-0.
[14] Yokoyama, T., Yamada, O., dan Nishimura, S.M., 1983. C 14 age Volcanic, Ashflow at Danan Island. Somma of Krakatoa Volcano, Indonesia, The Science and Engineering Review of Doshita University. Vol. 24, No. 1, May 1983.

[15] Deplus, C., Bonvalot, S., Dahrin, D., Diament, M., Harjono, dan Dubois, J., 1994, Inner Structure of the Krakatoa Volcanic Complex From Gravity and Bathymetry Data, Journal of Volcanology and Geothermal Research, 64, pg. 23-52.

[16] Judd, J.W., 1888, On the volcanic phenomena of the eruption, and on the nature and distribution of the ejected materials, Part I, In “The Eruption of Krakatoa Committee of the Royal Society”, G.J. Symons Ed. Harrison and Son, London. pg.1-66.