Morphological Changes of Anak Krakatau after the 22 December 2018 Flank Collapsed

Herlan Darmawan (herlan_darmawan@mail.ugm.ac.id)
Universitas Gadjah Mada Fakultas Matematika dan Ilmu Pengetahuan Alam https://orcid.org/0000-0001-6166-8272

Suratman Worosuprojo
Universitas Gadjah Mada Fakultas Geografi

Wahyudi Wahyudi
Universitas Gadjah Mada Fakultas Matematika dan Ilmu Pengetahuan Alam

Agung Harijoko
Universitas Gadjah Mada Fakultas Teknik

Haryo Edi Wibowo
Universitas Gadjah Mada Fakultas Teknik

Bachtiar W. Mutaqin
Universitas Gadjah Mada Fakultas Geografi

Nia Haerani
Center of Volcanology and Geological Hazards Mitigation

Syarifuddin Syarifuddin
Natural Resources Conservation Service

Milya Aflah Ulul Albab
Universitas Gadjah Mada Fakultas Matematika dan Ilmu Pengetahuan Alam

Raditya Jati
Indonesian National Board for Disaster Management

Wikanti Asriningrum
Indonesian National Institute of Aeronautics and Space: Lembaga Penerbangan dan Antariksa Nasional

---

Research Letter

Keywords: Morphological changes, Anak Krakatau, lava flow emplacement, reconstruction phase

Posted Date: February 24th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-230137/v1

Morphological changes of Anak Krakatau after the 22 December 2018 flank collapsed

Herlan Darmawan[1]*, Suratman Worosuprojo[2], Wahyudi[1], Agung Harijoko[3], Haryo Edi Wibowo[3], Bachtiar W. Mutaqin[2], Nia Haerani[4], Syarifuddin[5], Milya Aflah Ulul Albab[1], Raditya Jati[6], Wikanti Asriningrum[7]

1) Laboratory of Geophysics, Department of Physics, Faculty of Mathematics and Natural Sciences, Universitas Gadjah Mada, Sekip Utara, Bulaksumur, Yogyakarta, Indonesia
2) Department of Environmental Geography, Faculty of Geography, Universitas Gadjah Mada, Sekip Utara, Bulaksumur, Indonesia
3) Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Jl. Grafika No. 2, Yogyakarta 55281, Indonesia
4) Center for Volcanology and Geological Hazards Mitigation, Geological Agency, Ministry of Energy and Mineral Resources, Bandung, Indonesia
5) Bengkulu Natural Resource Conservation Agency, Jl. Z.A. Pagar alam No. 1B Rajabasa Bandar Lampung
6) Indonesian National Board for Disaster Management, Jl. Pramuka Kav. 38 Jakarta Timur 13120
7) Remote sensing application centre, National Institute of Aeronautics and Space of Indonesia, Pasar Rebo, Jakarta Timur, Indonesia

*) corresponding author: herlan_darmawan@mail.ugm.ac.id

Abstract

After the 22 December 2018 flank collapse, series of hydrothermal, phreatomagmatic, and effusive eruptions occurred and changed the morphology of Anak Krakatau. The ejected volcanic materials enlarge and increase the elevation of the west flank, which may indicate a reconstruction phase of the Anak Krakatau edifice. Here, we investigated the morphological changes of Anak Krakatau between 2019 and 2020 by using drone SfM photogrammetry, Sentinel and Pleiades satellite imageries, and fieldworks photograph data. The result shows volcaniclastic deposit due to the hydrothermal and/or phreatomagmatic eruptions that covered 0.08 km^2 around an active crater lake at Anak Krakatau between February and January 2020. The large phreatomagmatic and effusive eruptions on 10 April 2020 produced tephra and lava flow deposits that significantly changed the morphology of Anak Krakatau. The deposit of tephra covered 0.815 km^2 at the north – northwest flanks of Anak Krakatau, while the lava flow emplaced 0.2 km^2 and elongated around 742 m from the pre-existing crater lake to the west shoreline of Anak Krakatau. The lava flow has a blocky surface and highly fractured that possibly formed due to compression – extension stresses during lava flow emplacement. The emplacement of the massive lava flow at the pre-existing crater lake may change the future eruption style at Anak Krakatau, which was previously dominated by hydrovolcanism activities, such as hydrothermal and phreatomagmatic events.

Keywords: Morphological changes, Anak Krakatau, lava flow emplacement, reconstruction phase

Introduction

The flank collapsed of Anak Krakatau on 22 December 2018 was the most destructive volcanic event in the last decade. Approximately, 127×10^6 m^3 volume of the Anak Krakatau flank collapsed and caused a catastrophic tsunami in Sunda Strait (Darmawan et al. 2020; Williams et al. 2019; Ye et al. 2020). The generated tsunami reached a maximum height of 13 m and claimed 437 fatalities (Muhari et al. 2019). Shortly, after the devastating flank collapsed event in 2018, the morphology of Anak Krakatau has changed significantly. The pre-existing volcanic cone had collapsed and formed a large depression area with a crater lake as identified by post-collapse radar satellite imagery (Walter et al. 2019). High resolution bathymetry dataset after collapsed indicates that the material are deposited at the southwest seabed with thickness up to 70.4 m (Priyanto et al. 2021).

After the December 2018 catastrophic event, the activity of Anak Krakatau was dominated by hydrovolcanism activity at the crater lake where hydrothermal eruptions intermittently occurred in 2019. Between January and February 2020, a series of hydrothermal and/or phreatomagmatic activities at the crater lake produced steam-dominated and volcaniclastic materials with column eruption of up to 500 m, followed by a larger phreatomagmatic and effusive events on April 10th, 2020 (PVMBG 2020). After these eruptions, field observation conducted by Bengkulu Natural Resource Conservation Agency observed a massive lava flow deposit that elongated from the 2019 pre-existing volcanic crater lake to the west shoreline up to hundreds of meters and significantly changed the morphology of Anak Krakatau.

In this study, we documented for the first-time morphological changes of Anak Krakatau after the December 2018 catastrophic event. We used high-resolution UAV SfM aerial images orthomosaic that were acquired during fieldwork in August 2019, optical satellite images from Sentinel 2A and the Pleiades to observe morphological changes of Anak Krakatau and some fieldwork photographs between 2019 and 2020. UAV photogrammetry currently widely used for volcano monitoring (James et al. 2020), for lava dome morphology and instability (Darmawan et al. 2018; Darmawan et al. 2018), for volcanic gas measurements and ash cloud imaging (Gomez and Kennedy 2018; Liu et al. 2019; McGonigle et al. 2008), and volcano topographic changes

(Darmawan et al. 2017; Müller et al. 2017; Wahyudi et al. 2020) as UAV is very flexible to operate and able to produce high-quality aerial image datasets. While, Sentinel 2A constellation satellite is freely available with a revisit time of 10 days and can provide large geodatabase to monitor dynamic processes of the earth, includes volcano activities (Valade et al. 2019). Sentinel 2A has a pixel resolution of 10 m that can be used for large scale changes at an active volcano, such as in mapping lava flows at Mt. Etna, Italy (Corradino et al. 2019), while Pleiades satellite constellation that has a high resolution up to 0.5 m is able to monitor volcanic processes, such as lava flow emplacement at Fogo volcano, Cape Verde (Bagnardi et al. 2016).

Our datasets can explain the eruption processes that change the morphology of Anak Krakatau between 2019 and 2020. Monitoring of morphological changes at active marine stratovolcano such as Anak Krakatau is vital for volcanic hazard assessment, as the replacement of crater lake into massive lava flow deposit may change the near future mechanism of eruption at Anak Krakatau. Moreover, Anak Krakatau's edifice that is progressively reconstructed by its eruption's products, progressively grows, overstepping, and may be subjected to a gravitational load that causes flank instability and triggers tsunami in the next decades. Therefore, observation of morphological changes at an active marine stratovolcano should be systematically documented in order to mitigate volcano tsunami events worldwide.

Overview of Anak Krakatau

Anak Krakatau is an active volcano located in Sunda Strait, Indonesia, and lies along with an N20°E structure along Mt. Rajabasa – Sebuku – Sibesi – Panaitan islands (Fig. 1). The volcanism of Anak Krakatau is formed due to the subduction of the Indo-Australian plate beneath the Eurasian plate along Sumatran – Java islands, as indicated by shear wave seismic datasets (Harjono et al. 1989). The transition of oblique and almost orthogonal subduction between Sumatra and Java islands causes extension, rifting, and faulting around the Sunda Strait that may influence magma migration of Anak Krakatau (Harjono et al. 1991). Petrological and seismic studies suggest that Anak Krakatau has a shallow magma chamber complex at a depth of 2 – 8 km which may influence the eruption style of Anak Krakatau (Dahren et al. 2011; Gardner et al. 2013; Jaxybulatov et al. 2011).

After the global catastrophic of the Krakatau eruption in 1883, the emerging of the Anak Krakatau edifice was successfully captured in 1927 (Stehn 1929). The recent Anak Krakatau location is controlled by the 1883 vent and conduit of the Krakatau volcano (Self and Rampino 1981). Since then, the morphological evolution of Anak Krakatau is well documented through conventional sketched and topographic surveys between 1930 and 1990 (Decker and Hadikusumo 1961; Zen 1969). During that period, the edifice of Anak Krakatau was subjected to constructive and destructive phases. Morphological sketched between 1930 and 1935 documented an early reconstruction phase of the crater rim and lake at Anak Krakatau (Zen 1969). A large eruption in 1936 destroyed and removed volcanic materials at the crater lake, which may indicate the first destructive phase (Zen 1969). Detail topographic surveys between 1950 and 1960 clearly recorded the reconstruction stage of the Anak Krakatau edifice due to massive volcanic deposits of intermittent eruptions (Decker and Hadikusumo 1961). In 1952, a crater lake formed with a diameter of ~300 m that delineated by the old rim with a maximum elevation of 151.5 m. The intermittent eruption produced blocks – bombs, volcaniclastic, and tephra were mainly deposited around the crater lake and formed a volcanic cone in 1960 (Decker and Hadikusumo 1961). Then, the activities of Anak Krakatau between the 1970s and 1990s were dominated by lava flows that mostly emplaced at the west – south flanks area and pyroclastic deposits (Abdurrachman et al. 2018; Sutawidjaja 1997). Some of the 1992, 1993, and 1996 lava flows emplaced at the north of Anak Krakatau edifice (Sutawidjaja 1997; Sutawidjaja 2006). The reconstruction of Anak Krakatau continuously occurred and reached maximum elevation at the crater rim up to ~300 m in 1996 (Sutawidjaja 1997). The type of eruptions were then dominated by strombolian in 2000’s and prior to the 2018 flank collapsed event (Gardner et al. 2013; Perttu et al. 2020).

Results

Morphological changes of Anak Krakatau between 2019 and 2020

High-resolution drone orthomosaic aerial images, sentinel 2A, and Pleiades satellite imageries clearly observed morphological changes of Anak Krakatau between August 2019 and May 2020. In August 2019, the edifice of Anak Krakatau was about 3 km^2 above sea level with a crater lake of 0.13 $km^{2,}$ and the diameter of the crater lake was about 430 m (Fig. 3a and b). Most of the Anak Krakatau edifice was covered by the December 2018 eruptions material that eroded and formed stream flows. Our high-resolution drone orthomosaic also observed altered rock and some blocks – bombs deposit at the west part of the volcanic crater (Fig. 3b). During our fieldwork in August 2019, we observed intermittent hydrothermal eruptions that ejected small-scale volcanic gas and mud around the crater lake (Fig. 4a and b).

In February 2020, changes were observed at the crater lake of Anak Krakatau (Fig. 3c and d). Series of hydrothermal and/or phreatomagmatic eruptions between January and February 2020 produced volcaniclastic materials that mostly deposited around Anak Krakatau crater lake and changed the morphology of the crater lake. The volcaniclastic materials covered around 0.08 km^2 and reduce the diameter of the crater lake of Anak Krakatau from 430 to 213 m. The volcaniclastic deposit formed such a small cone, as shown by our fieldwork photograph on 26 March and 15 August 2020 in Fig. 4c and d, respectively. The temperature of the active crater lake is possibly high as it regularly releases hot steam as observed from field photograph (Fig. 4c).

The morphology of Anak Krakatau has dramatically changed due to large phreatomagmatic, which was followed by an effusive eruption that occurred on 10 April 2020, as shown from

Pleiades satellite imagery and fieldwork photograph (Fig. 3e and 4d). By using supervised image classification, we mapped tephra deposits that cover 0.815 km^2 at the north – northwest flanks of Anak Krakatau edifice (as indicated by the grey color at Fig. 3f). The eruption also produced a lava flow that emplaced from the Anak Krakatau main conduit to the west flank up to 742 m distance. The coverage area of the lava flow deposit is around 0.2 km^2. About half of the lava flow deposit has widened the Anak Krakatau edifice from 3 to 3.1 km^2 above mean sea level. We quantified the mean thickness of the lava flow is about ~50 m based on the fieldwork photograph (Fig. 4 and 5) and estimate the bulk volume of lava flow deposit is ~11.2×10^6 m^3.

Morphology and structure of lava flow

A combination of 4, 3, 1 on RGB bands of Pleiades high-resolution satellite imagery and field photographs can provide detail morphology and structure of lava flow at Anak Krakatau (Fig. 4 and 5). The outer part of the lava flow is rough, blocky, and consists of large fragments with a diameter >0.5 m (Fig. 4e and f). The lava flow surface and the fragments have red dominated color which caused by oxidation processes during emplacement. Analysis of structural density indicates two main compression areas with up to 4 structures/m^2 located close to the west shoreline and the main crater. While, the middle part of the lava flow is not highly fractured with ~2 structures/m^2, which indicating an extension process (Fig. 4).

Discussion

Recent morphological changes of Anak Krakatau indicate a reconstruction phase after the 22 December flank collapsed (Darmawan et al., 2020). The reconstruction phase is strongly controlled by hydrovolcanism activity between August 2019 and April 2020 and effusive eruptions that occurred shortly after the phreatomagmatic event on 10 April 2020. Hydrovolcanism is a volcanic process related to direct or indirect interaction between magma and water that can trigger explosives to the non-explosive eruption (Németh and Kósik 2020; Sheridan and Wohletz 1983). Here, we purpose three stages of hydrovolcanism processes at Anak Krakatau that possibly occurred between 2019 and 2020 and changed the morphology of Anak Krakatau (Fig. 6).

The first stage is intermittent small scale hydrothermal or phreatic eruptions. During our fieldwork in August 2019, hydrothermal eruptions that produced mostly hot steam and a small volume of mud (possibly pre-existing materials) frequently occurred for almost every hour with different intensity as captured by our drone aerial and fieldwork image (Fig. 4 a and b). Similar activity occurred at White Island volcano, New Zealand (Edwards et al. 2017). In 2013, when hydrothermal or phreatic eruptions episode ejected steam-dominated and vertical mud materials up to 50 m high, these eruptions were clearly documented by high-resolution photos and video (Edwards et al. 2017).

The second stage is a transition of hydrothermal – phreatomagmatic eruptions between January and February 2020 that produced a small volcanic cone. Since we lack information on juvenile samples, it is difficult to conclude whether the eruptions were caused by direct or indirect contact of magma–water interaction. However, the volume of ejected mud is much higher compared to the 2019 hydrothermal activities, which may suggest an increase of thermal stress due to magma ascending. Another evidence of magma ascending is the formation of a continuous water bubble. On 30 March 2020, Bengkulu Natural Resource Conservation Agency observed large water bubbles at the east part of Anak Krakatau edifice, which may indicate an active degassing underwater fracture. These continuous water bubbles might be a strong precursor of the April 2020 phreatomagmatic eruption at Anak Krakatau as magma continuously rises. The magma temperature may drop, cools, and releases some volatiles that causing intense degassing (Burgisser and Degruyter 2015).

The third stage is a large explosive phreatomagmatic eruption that is followed by an effusive eruption. The direct interaction of magma – water lake of Anak Krakatau removed pre-existing unconsolidated volcanic materials and produced tephra deposit. The removal of volcanic materials at the conduit may facilitate magma to ascend and produced blocky lava flow.

The emplacement of lava flow deposits at Anak Krakatau is strongly controlled by pre-existing topography and its rheology. We overlaid the lava flow deposit on the pre-existing DEM and observed that the lava flow came out from the 2020 crater lake (Fig. 7a). We infer that the 2020 crater lake is the main conduit at the current Anak Krakatau edifice as hydrothermal eruptions were previously located in this area. The main flow of lava traveled to the west – southwest – south direction and reached a topography barrier at the southwest area with a slope of up to 50°. As the lava flow continuously occurred, some lava traveled to the southeast and form the first lava levee (lava levee I in Fig. 7). Some mass of lava flow moved to the west (shoreline) direction. Interaction between hot lava and seawater caused rapid cooling, solidified the lava, halted the movement of the lava flow, and formed lava levee II. As the lava was solidified at the shoreline and the volume of lava continuously pushed to the west, compression structure occurred, and some lava migrates to the north and formed lava levee III. This migration caused an extension zone, and therefore, the intensity of fractures is low.

Conclusion

Anak Krakatau is an active marine stratovolcano where its edifice consists of eruptions products and frequently undergoes constructive – destructive phases. Recent morphological changes may indicate a construction phase of the Anak Krakatau edifice due to hydrovolcanism and effusive activities. The series of hydrovolcanism events that occurred between 2019 and early 2020 ejected mostly pre-existing of the 2018 volcanic materials that formed a small volcanic cone at the Anak Krakatau crater lake. The phreatomagmatic and effusive events on 10 April 2020 dramatically changes the morphology of Anak Krakatau as a massive lava flow deposit with an estimated thickness of 3 – 70 m reconstructed the west flank area and has extended the edifice of Anak Krakatau ~0.1 km above mean sea level. The 2019 – 2020 activities of Anak Krakatau are relevant to the historical events, where most of the eruption sites were mostly constrained at the crater lake. Therefore, we infer that the 2019 crater lake is the main conduit of Anak Krakatau. The 2019 crater lake is currently replaced by the massive deposit of lava flow which may change the mechanism and type of eruption in the near future.

Data and Method

Drone photogrammetry data acquisition

We conducted UAV data acquisition in August 2019 or during summertime in Indonesia to obtain the best visibility of Anak Krakatau. We used a DJI Mavic drone capable of flying up to 500 m above the ground and a maximum distance of 8 km. The diameter of the Anak Krakatau edifice is about 2 km from east to west, and by setting the drone altitude up to ~350 m, we can cover the whole edifice (see Fig. 2 for the coverage area of drone data acquisition). We obtained about ~2,000 geotagged drone images that can be used to reconstruct high-resolution aerial images orthomosaic and Digital Elevation Model.

Reconstructing high-resolution orthomosaic

The UAV images are processed using the Structure from Motion (SfM) technique (Szeliski 2010), which is implemented in agisoft photoscan software, to generate Digital Elevation Model and Orthomosaic. We first imported all the drone images and ran image alignment function with the highest accuracy, reference pair selection, and key point limit to 40,000. The image alignment function reads the camera parameters, positions, and identifies the common points on images, matches them, and results in a 3D sparse point cloud. The next step is generating a 3D dense point cloud by set quality parameters to high and depth filtering to medium. This parameter can sort out outliers and reduce computational time. The 3D dense point cloud data set was then used as an input to generate a 3D mesh. The 3D mesh is necessary to reconstruct the Digital Elevation Model of Anak Krakatau. Further processing, we applied a texture and a tiled model to smooth the surface and to reconstruct a high-resolution orthomosaic of Anak Krakatau. The drone aerial orthomosaic image has a resolution of 0.08 m that can clearly identify the morphology of Anak Krakatau.

Satellite images dataset

We used two optical multispectral satellite images, Sentinel 2A and high-resolution Pleiades satellite images. Sentinel 2A has 13 bands, a pixel resolution of ~10 m, and a revisit time of 10 days that can be used to observed large changes at Anak Krakatau. Sentinel 2A is freely available and can be download at Sentinel open access data hub. While the Pleiades is a commercial multispectral optical satellite constellation that can provide very high resolution (0.5 m) and can be used for the morphological analysis of Anak Krakatau post 10 April 2020 eruption in further detail. The main obstacle of an optical satellite is the cloud that can reduce the visibility of the Anak Krakatau edifice. However, we obtained a free cloud for sentinel 2A and Pleiades satellite imagery that was acquired on 22 February and 30 May 2020, respectively for morphological changes analysis.

Orthomosaic and satellite data analysis

High-resolution drone aerial orthomosaic, sentinel 2A, and Pleiades satellite images can provide detailed morphology of Anak Krakatau edifice and lava flow deposits. We manually digitized the morphological changes of coastline, crater lake, and lava flow at Anak Krakatau between 2019 and 2020 that clearly visible from aerial drone orthomosaic and satellite images. For the Pleiades satellite image, we opened the image on arcmap and visualized it by a combination of RGB band of 4, 3, 1 and alpha band of 1 to obtain the best visualization of the lava flow structure. We manually digitized the clearly visible structures and generated a density of structural map to further analyze the rheology behavior of lava flow at Anak Krakatau.

Moreover, we mapped tephra deposits due to the 10 April 2020 eruption. We firstly took some samples pixel value on tephra deposit in Pleiades satellite image and automatically classified them using supervised image classification in ArcMap software. This automatic supervised classification can rapidly map the hazard zone due to volcanic eruptions. The classified raster image was converted into a polygon dataset to estimate the deposit area of tephra due to the 10 April 2020 eruption at Anak Krakatau.

Availability of data

The datasets used and/or analysed during this study are available from the corresponding author on reasonable request.

Acknowledgments

We thank the Nature Conservation Agency of Bengkulu Province for the permission, the boat, and accommodation during fieldwork at Anak Krakatau Volcano in 2019 and 2020.

Funding

This study is funded by the Indonesian Ministry of Education and Research's program of Insentif Riset Sistem Inovasi Nasional (INSINAS) number 06/INS-2/PPK/E4/2020.

Competing interests

We declare no competing interests

Contributions

H.D. processed the drone dataset, interpreted all of the morphological and structural changes, and write the first draft. S.W. led the project and improved the manuscript. M. A. U. A. processed and digitized the pleiades satellite image. W, A.H., H. E. W., B.W.M., N. H., S., R. J., W. A., improved the manuscript and supported some field work photographs.

References

Abdurrachman M, Widiyantoro S, Priadi B, Ismail T (2018) Geochemistry and Structure of Krakatoa Volcano in the Sunda Strait, Indonesia. Geosciences 8(4):111. doi: 10.3390/geosciences8040111.

Bagnardi M, González PJ, Hooper A (2016) High-resolution digital elevation model from tri-stereo Pleiades-1 satellite imagery for lava flow volume estimates at Fogo Volcano. Geophysical Research Letters 43(12):6267-6275. doi: https://doi.org/10.1002/2016GL069457.

Burgisser A, Degruyter W (2015) Magma ascent and degassing at shallow levels. In: Sigurdsson H, Houghton B, McNutt SR, Rymer H, Stix J (eds) The Encyclopedia of Volcanoes. Elsevier, Amsterdam

Corradino C, Ganci G, Cappello A, Bilotta G, Hérault A, Del Negro C (2019) Mapping Recent Lava Flows at Mount Etna Using Multispectral Sentinel-2 Images and Machine Learning Techniques. Remote Sensing 11(16):1916. doi: 10.3390/rs11161916.

Dahren B, Troll VR, Andersson UB, Chadwick JP, Gardner MF, Jaxybulatov K, Koulakov I (2011) Magma plumbing beneath Anak Krakatau volcano, Indonesia: evidence for multiple magma storage regions. Contributions to Mineralogy and Petrology 163(4):631-651. doi: 10.1007/s00410-011-0690-8.

Darmawan H, Mutaqin BW, Wahyudi, Harijoko A, Wibowo HE, Haerani N, Surmayadi M, Syarifudin, Suratman, Asriningrum W (2020) Topography and structural changes of Anak

Krakatau due to the December 2018 catastrophic events. Indonesian Journal of Geography 52(3):402 - 410. doi: https://doi.org/10.22146/ijg.53740.

Darmawan H, Walter TR, Brotopuspito KS, Subandriyo, Nandaka IGMA (2018) Morphological and structural changes at the Merapi lava dome monitored in 2012–15 using unmanned aerial vehicles (UAVs). Journal of Volcanology and Geothermal Research 349:256-267. doi: 10.1016/j.jvolgeores.2017.11.006.

Darmawan H, Walter TR, Richter N, Nikkoo M (2017) High resolution Digital Elevation Model of Merapi summit in 2015 generated by UAVs and TLS. GFZ Data Services. doi: http://doi.org/10.5880/GFZ.2.1.2017.003.

Darmawan H, Walter TR, Troll VR, Budi-Santoso A (2018) Structural weakening of the Merapi dome identified by drone photogrammetry after the 2010 eruption. Natural Hazards and Earth System Sciences 18(12):3267-3281. doi: 10.5194/nhess-18-3267-2018.

Decker RW, Hadikusumo D (1961) Results of the 1960 expedition to Krakatau. Journal of Geophysical Research 66:3497-3511. doi: 10.1029/jz066i010p03497.

Edwards MJ, Kennedy BM, Jolly AD, Scheu B, Jousset P (2017) Evolution of a small hydrothermal eruption episode through a mud pool of varying depth and rheology, White Island, NZ. Bulletin of Volcanology 79(2). doi: 10.1007/s00445-017-1100-5.

ESRI, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, Community tGU (2012) "Topographic" [basemap]. Scale Not Given. "World Topographic Map". In,

Gardner MF, Troll VR, Gamble JA, Gertisser R, Hart GL, Ellam RM, Harris C, Wolff JA (2013) Crustal differentiation processes at Krakatau Volcano, Indonesia. Journal of Petrology 54:150-182. doi: 10.1093/petrology/egs066.

Gomez C, Kennedy B (2018) Capturing volcanic plumes in 3D with UAV-based photogrammetry at Yasur Volcano – Vanuatu. Journal of Volcanology and Geothermal Research 350:84-88. doi: https://doi.org/10.1016/j.jvolgeores.2017.12.007.

Harjono H, Diament M, Dubois J, Larue M, Zen MT (1991) Seismicity of the Sunda Strait: Evidence for crustal extension and volcanological implications. Tectonics 10:17-30. doi: 10.1029/90TC00285.

Harjono H, Diament M, Nouaili L, Dubois J (1989) Detection of magma bodies beneath Krakatau volcano (Indonesia) from anomalous shear waves. Journal of Volcanology and Geothermal Research 39:335-348. doi: https://doi.org/10.1016/0377-0273(89)90097-8.

James M, Carr B, D'Arcy F, Diefenbach A, Dietterich H, Fornaciai A, Lev E, Liu E, Pieri D, Rodgers M, Smets B, Terada A, von Aulock F, Walter T, Wood K, Zorn E (2020) Volcanological applications of unoccupied aircraft systems (UAS): Developments, strategies, and future challenges. Volcanica:67-114. doi: 10.30909/vol.03.01.67114.

Jaxybulatov K, Koulakov I, Seht MI-v, Klinge K, Reichert C, Dahren B, Troll VR (2011) Evidence for high fluid/melt content beneath Krakatau volcano (Indonesia) from local earthquake tomography. Journal of Volcanology and Geothermal Research 206:96-105. doi: https://doi.org/10.1016/j.jvolgeores.2011.06.009.

Liu EJ, Wood K, Mason E, Edmonds M, Aiuppa A, Giudice G, Bitetto M, Francofonte V, Burrow S, Richardson T, Watson M, Pering TD, Wilkes TC, McGonigle AJS, Velasquez G, Melgarejo C, Bucarey C (2019) Dynamics of Outgassing and Plume Transport Revealed by Proximal Unmanned Aerial System (UAS) Measurements at Volcán Villarrica, Chile. Geochemistry, Geophysics, Geosystems 20:730-750. doi: 10.1029/2018GC007692.

McGonigle AJS, Aiuppa A, Giudice G, Tamburello G, Hodson AJ, Gurrieri S (2008) Unmanned aerial vehicle measurements of volcanic carbon dioxide fluxes. Geophysical Research Letters 35. doi: 10.1029/2007GL032508.

Muhari A, Heidarzadeh M, Susmoro H, Nugroho HD, Kriswati E, Supartoyo, Wijanarto AB, Imamura F, Arikawa T (2019) The December 2018 Anak Krakatau Volcano Tsunami as Inferred from Post-Tsunami Field Surveys and Spectral Analysis. Pure and Applied Geophysics 176:5219-5233. doi: 10.1007/s00024-019-02358-2.

Müller D, Walter TR, Schöpa A, Witt T, Steinke B, Gudmundsson MT, Dürig T (2017) High-resolution digital elevation modeling from TLS and UAV campaign reveals structural complexity at the 2014/2015 Holuhraun Eruption site, Iceland. Frontiers in Earth Science 5:1-15. doi: 10.3389/feart.2017.00059.

Németh K, Kósik S (2020) Review of Explosive Hydrovolcanism. Geosciences 10(2):44. doi: 10.3390/geosciences10020044.

Perttu A, Caudron C, Assink JD, Metz D, Tailpied D, Perttu B, Hibert C, Nurfiani D, Pilger C, Muzli M, Fee D, Andersen OL, Taisne B (2020) Reconstruction of the 2018 tsunamigenic flank collapse and eruptive activity at Anak Krakatau based on eyewitness reports, seismo-acoustic and satellite observations. Earth and Planetary Science Letters 541:116268. doi: 10.1016/j.epsl.2020.116268.

Priyanto WS, Hunt JE, Hanif M, Tappin DR, Permana H, Susilohadi, Cassidy M, Yulianto E (2021) Bathymetry and Shallow Seismic Imaging of the 2018 Flank Collapse of Anak Krakatau. Frontiers in Earth Science 8. doi: 10.3389/feart.2020.577448.

PVMBG (2020) Press Release Aktivitas G. Anak Krakatau 11 April 2020. In: PVMBG, Bandung, Indonesia

Self S, Rampino MR (1981) The 1883 eruption of Krakatau. Nature 294(5843):699-704. doi: 10.1038/294699a0.

Sheridan MF, Wohletz KH (1983) Hydrovolcanism: Basic considerations and review. Journal of Volcanology and Geothermal Research 17(1):1-29. doi: https://doi.org/10.1016/0377-0273(83)90060-4.

Stehn CE (1929) The geology and volcanism of the Krakatau Group. In: In: Guidebook for 4th Pac Sci Congr. Batavia, pp 1 - 55

Sutawidjaja I (1997) The activities of Anak Krakatau volcano during the years of 1992-1996. In: The Disaster Prevention Research Institute Annuals. pp 13-22

Sutawidjaja I (2006) Pertumbuhan Gunung Api Anak Krakatau setelah letusan katastrofi s 1883. Indonesian Journal on Geoscience 1:143-153. doi: 10.17014/ijog.vol1no3.20063.

Szeliski R (2010) Computer Vision: Algorithms and Applications.1 - 979.

Valade S, Ley A, Massimetti F, D'Hondt O, Laiolo M, Coppola D, Loibl D, Hellwich O, Walter TR (2019) Towards Global Volcano Monitoring Using Multisensor Sentinel Missions and Artificial Intelligence: The MOUNTS Monitoring System. Remote Sensing 11(13):1528. doi: 10.3390/rs11131528.

Wahyudi, Setiawan A, Putra H, Darmawan H, Suyanto I, Meilano I, Irzaman, Evita M, Djamal M, Yasin M, Aminah NS, Perdinan, Apsari R, Srigutomo W, Suryanto W (2020) Topography changes and thermal distribution at the Kelud crater after the 2014 Plinian eruption. Indonesian Journal of Geography 52(3):411 - 417. doi: https://doi.org/10.22146/ijg.51986.

Walter TR, Haghshenas Haghighi M, Schneider FM, Coppola D, Motagh M, Saul J, Babeyko A, Dahm T, Troll VR, Tilmann F, Heimann S, Valade S, Triyono R, Khomarudin R, Kartadinata N, Laiolo M, Massimetti F, Gaebler P (2019) Complex hazard cascade culminating in the Anak Krakatau sector collapse. Nature Communications 10. doi: 10.1038/s41467-019-12284-5.

Williams R, Rowley P, Garthwaite MC (2019) Reconstructing the Anak Krakatau flank collapse that caused the December 2018 Indonesian tsunami. Geology XX:1-4. doi: 10.1130/g46517.1.

Ye L, Kanamori H, Rivera L, Lay T, Zhou Y, Sianipar D, Satake K (2020) The 22 December 2018 tsunami from flank collapse of Anak Krakatau volcano during eruption. Science Advances 6(3):eaaz1377. doi: 10.1126/sciadv.aaz1377.

Zen MT (1969) The state of Anak Krakatau in September 1968. Bulletin of National Institute of Geology and Mining 2:15 - 23.

Figures

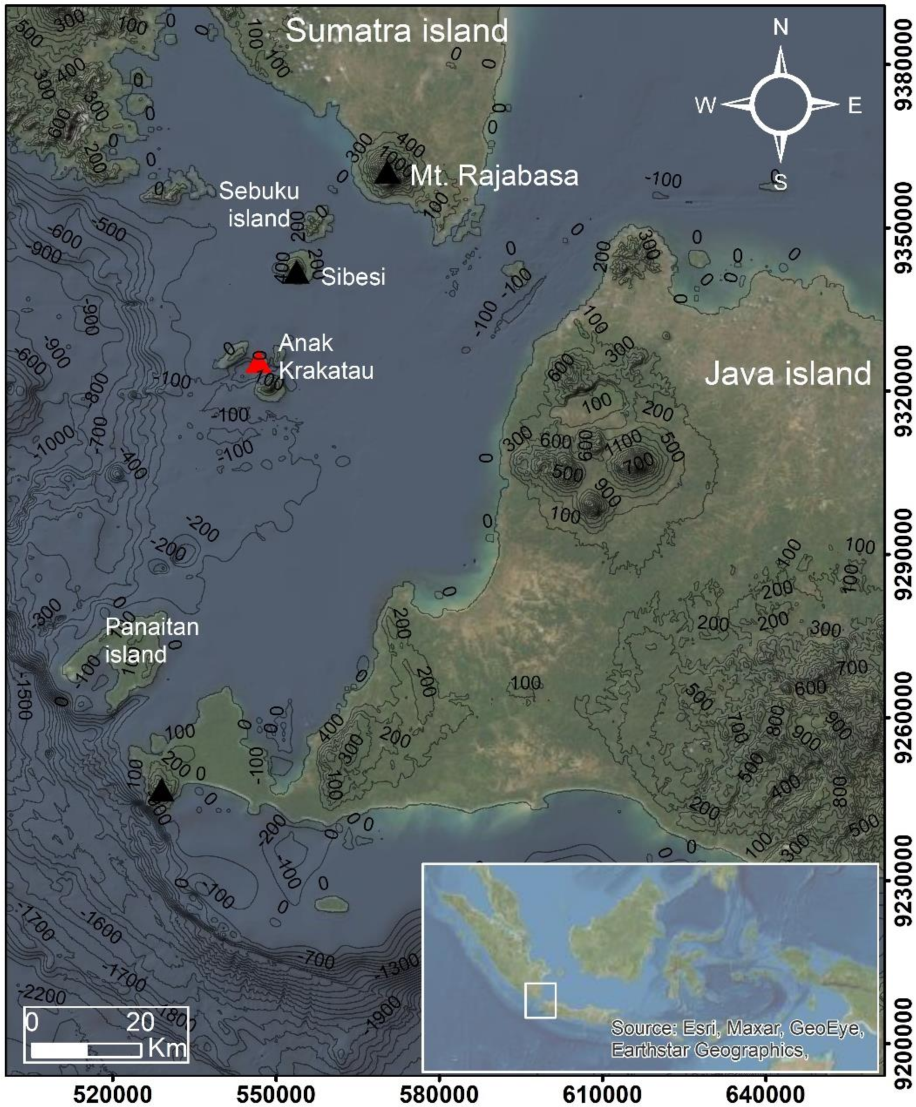

Figure 1. Anak Krakatau is an active marine volcano located in Sunda Strait (between Sumatra and Java Island, Indonesia in inset) (ESRI et al. 2012). The famous event was recorded in 1883 when the eruption of Krakatau triggered a catastrophic global tsunami that caused almost 36,000 fatalities (Self and Rampino 1981). Around 135 years later, a flank collapsed of Anak Krakatau triggered a tsunami in Sunda Strait on 22 December 2018 that caused hundreds of lives lost.

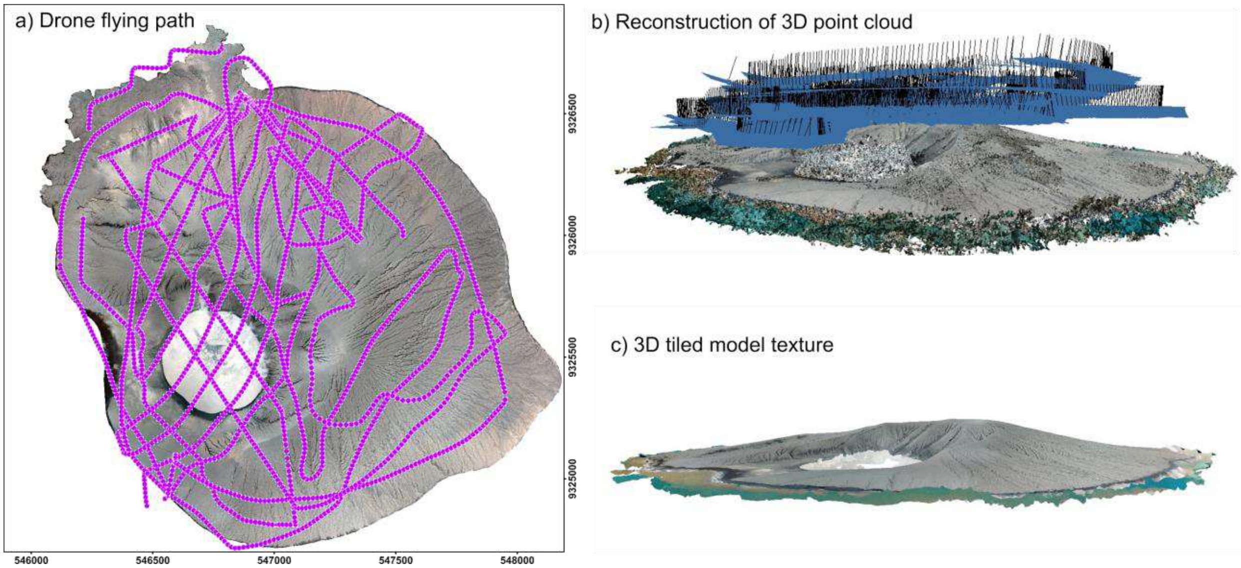

Figure 2. a) coverage area of aerial images taken by the drone. The purple dots indicate the location of aerial drone image data sampling. b) By using structure from motion algorithm, we can derive 3D dense point cloud that can be further processed to obtain c) 3D tiled model texture. This model can be exported as Digital Elevation Model and orthomosaic data for morphological and structural analysis.

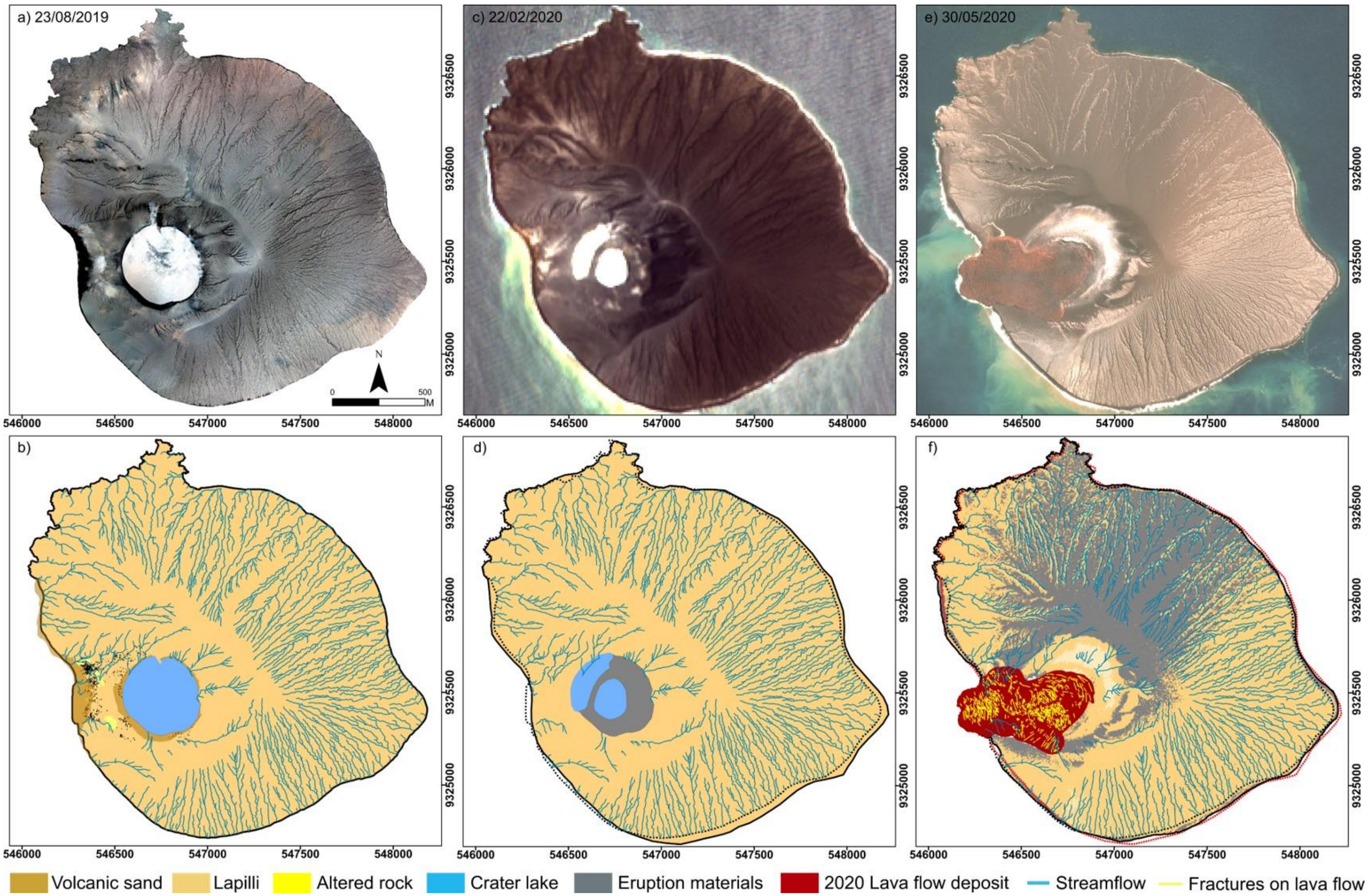

Figure 3. Morphological changes of Anak Krakatau between a-b) August 2019, c-d) February and e-f) May 2020.

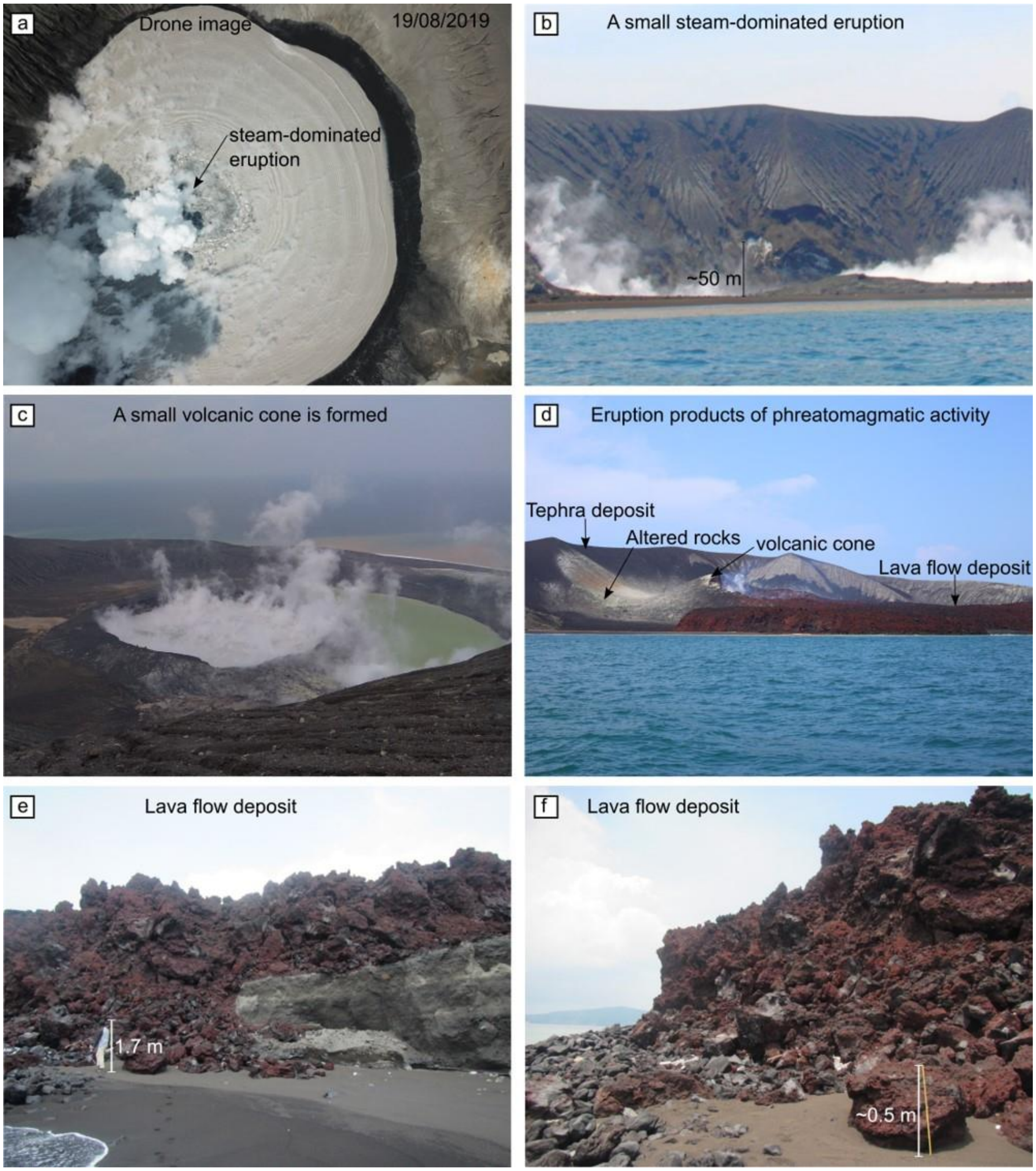

Figure 4. a-b) A hydrothermal eruption that occurred at Anak Krakatau produced steam dominated eruption in 2019. b) Series of hydrothermal and/or phreatomagmatic eruptions that occurred between January and February 2020 has formed a small volcanic cone at the crater lake of Anak Krakatau. d) Large phreatomagmatic and effusive eruptions ejected volcanic tephra and lava flow deposit at the west flank area of Anak Krakatau. e-f) Close observation of lava flow deposit shows surface blocky and some large fragments of a lava flow during emplacement.

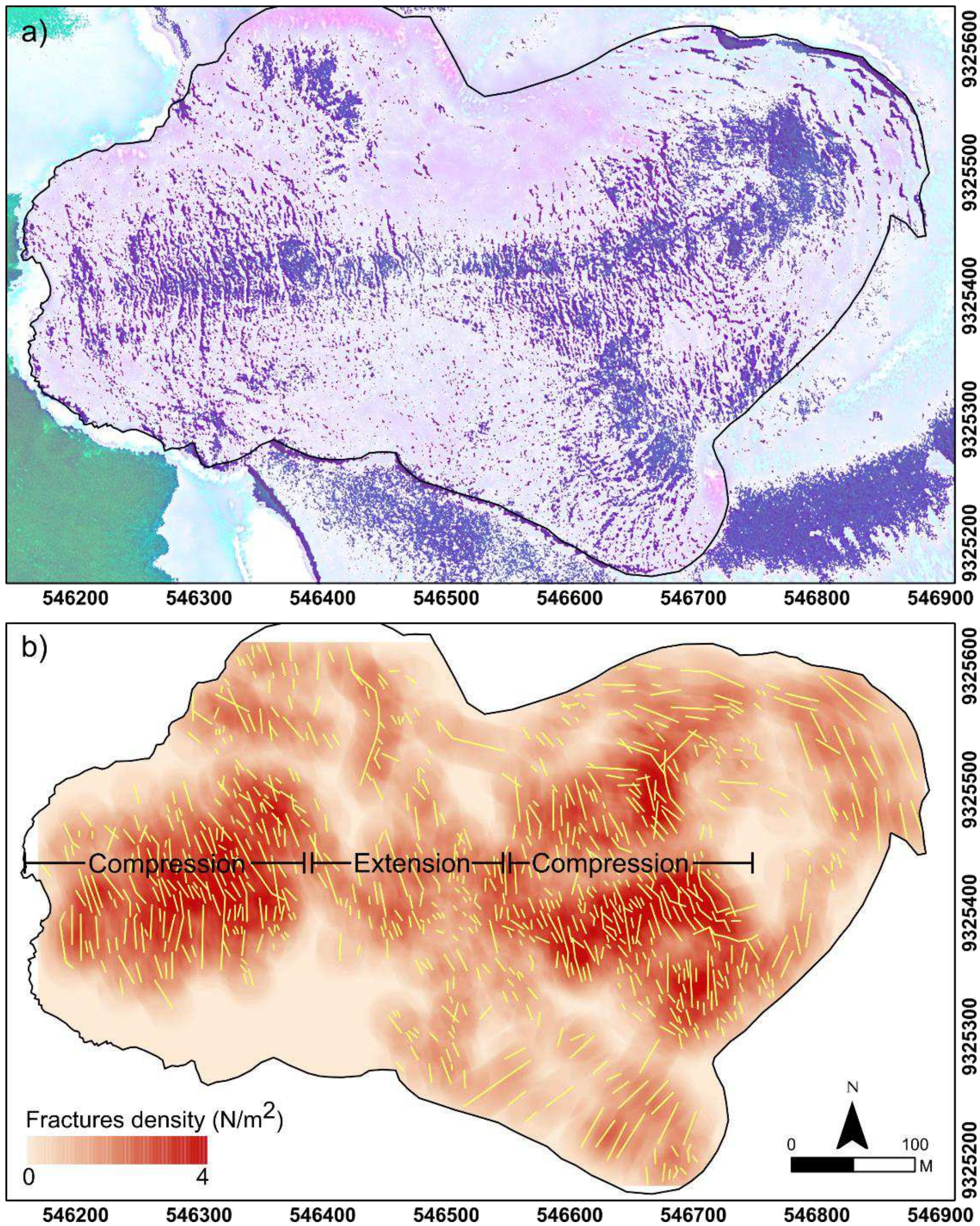

Figure 5. a) A combination of 4, 3, 1 on RGB bands of Pleiades satellite image provides detailed structures of the lava flow at Anak Krakatau. b) structural analysis shows some areas that undergo compression – extension – compression at lava flow of Anak Krakatau.

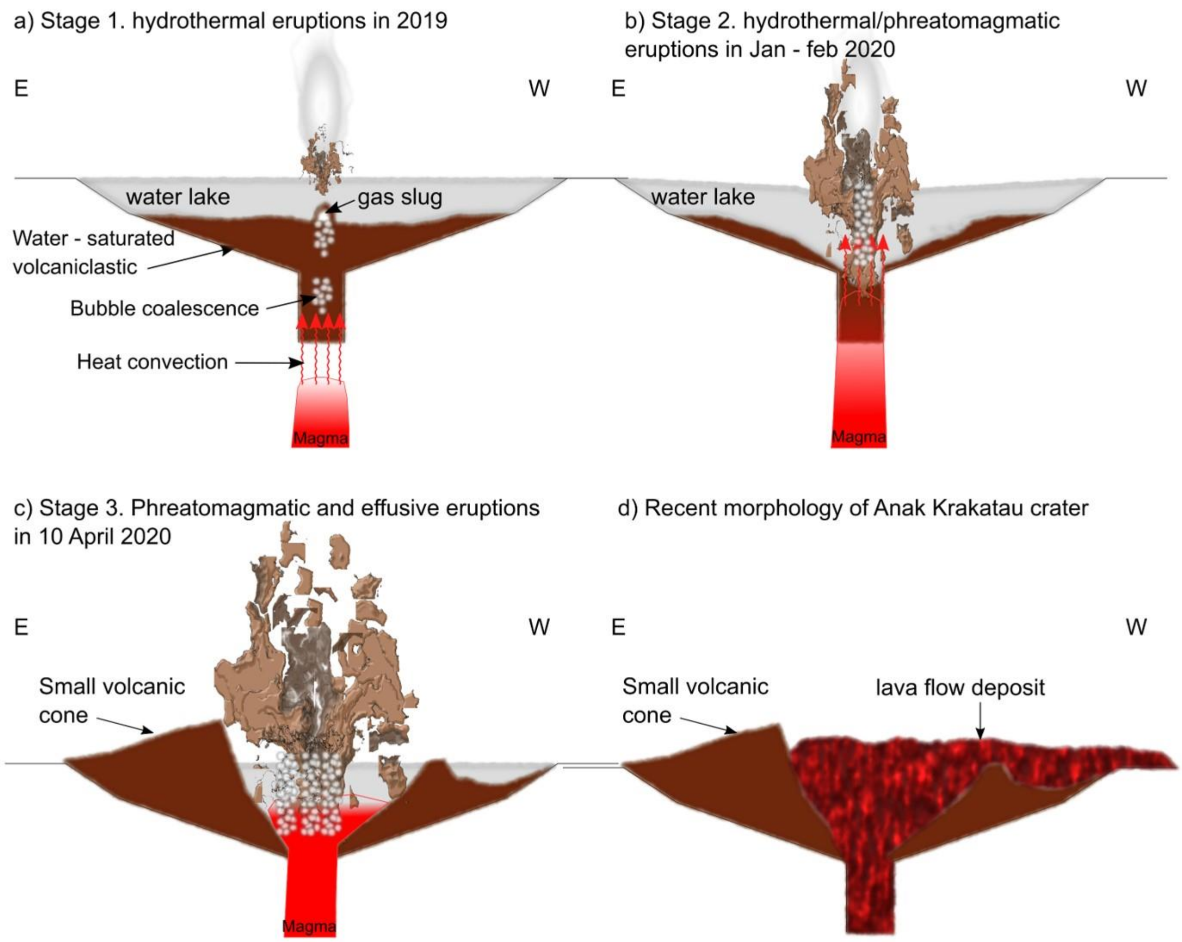

Figure 6. Morphological changes of the Anak Krakatau edifice that occurred between 2019 and 2020 are strongly controlled by hydrovolcanism activities that consist of a) hydrothermal eruptions in 2019, b) hydrothermal and/or phreatomagmatic eruptions between January and February 2020, c) Large phreatomagmatic and effusive eruptions on 10 April 2020. d) The last event produced a massive lava flow deposit that significantly reconstructs the west edifice of Anak Krakatau.

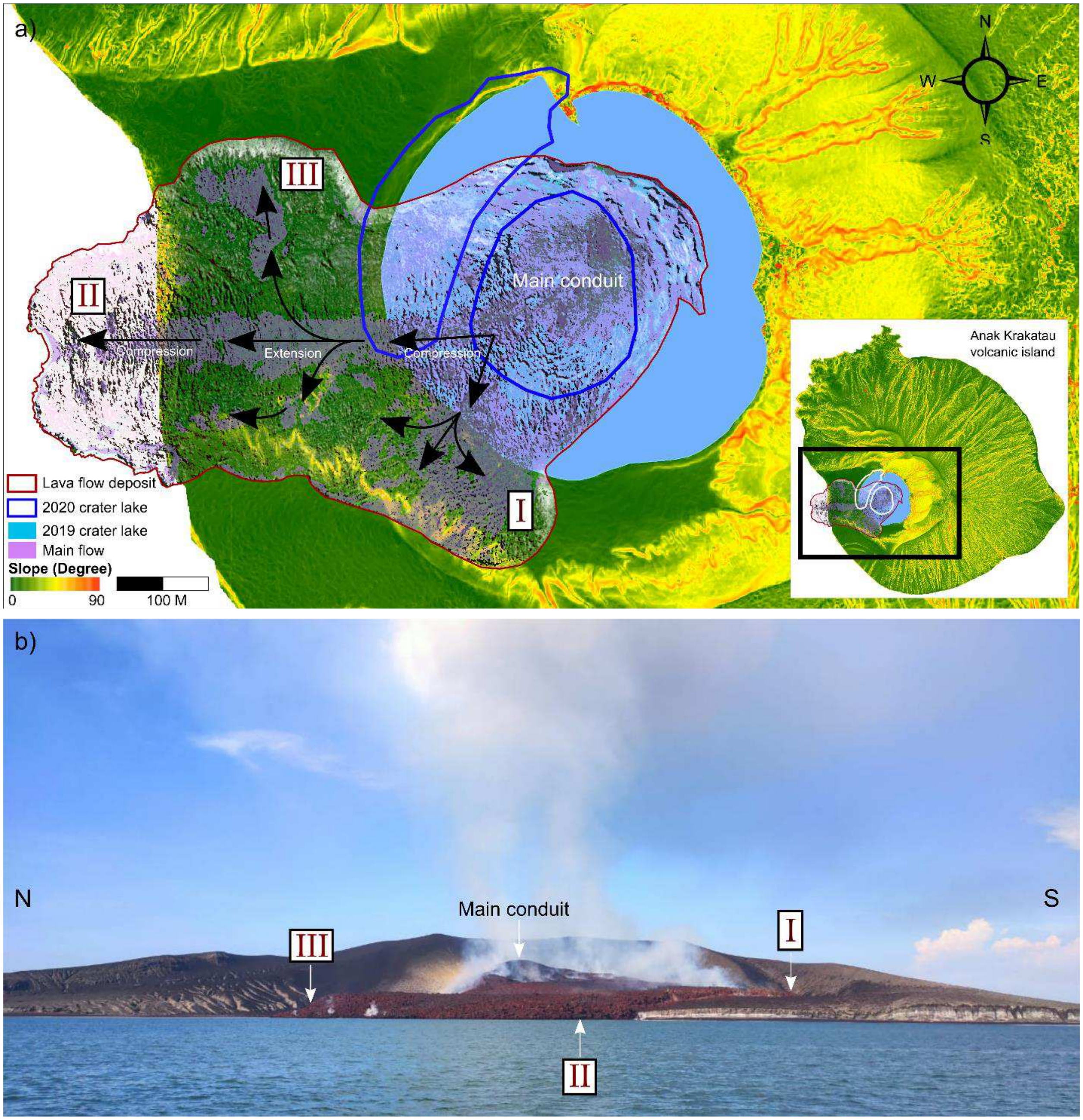

Figure 7. The emplacement of a lava flow is strongly controlled by the basal surface. a) Overlay of lava flow deposit on slope map suggests that most of the lava flow has deposited at a low slope topography profile. b) The lava flow has three lava levees, as observed by field photographs and satellite imageries.

Figures

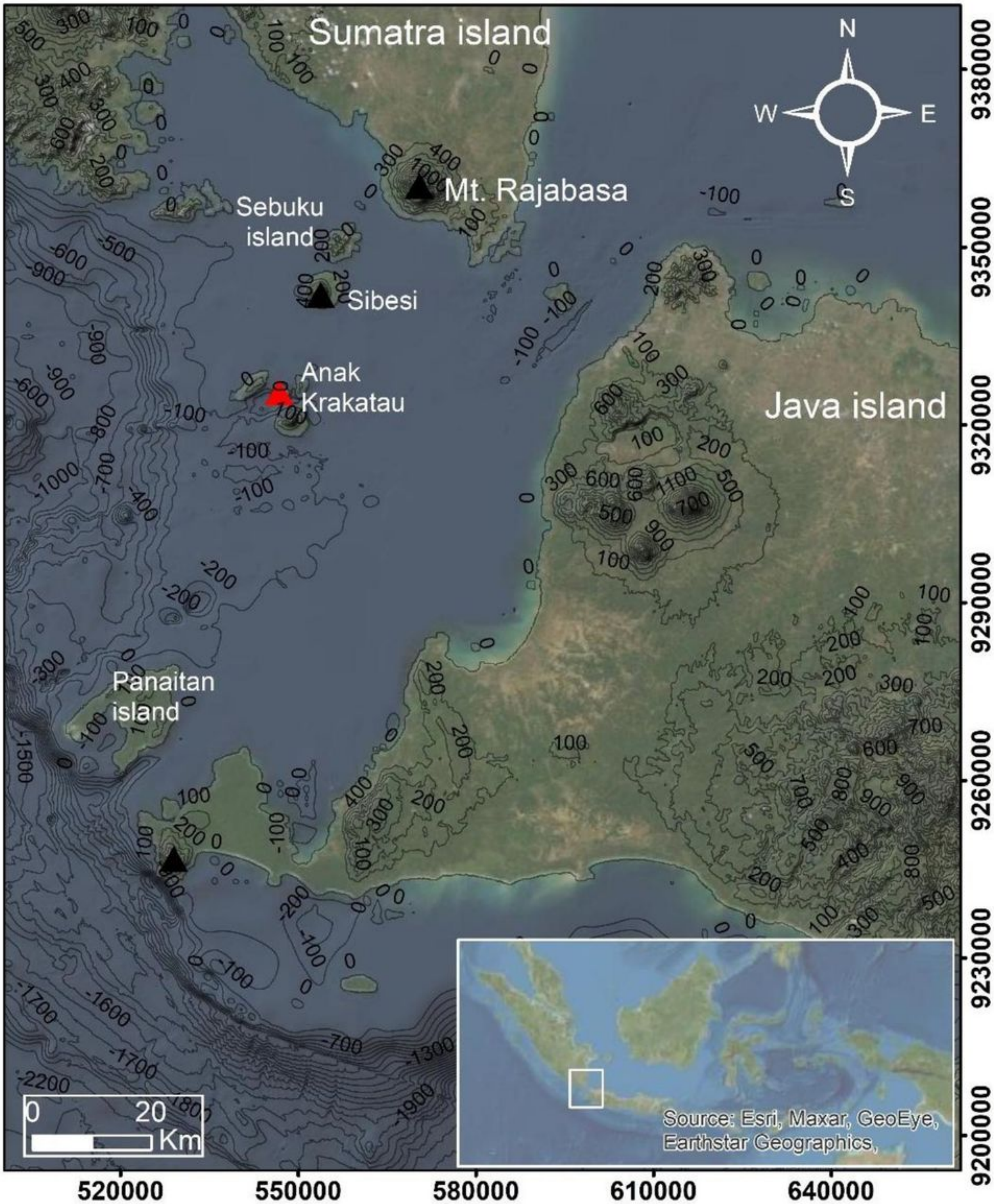

Figure 1

Anak Krakatau is an active marine volcano located in Sunda Strait (between Sumatra and Java Island, Indonesia in inset) (ESRI et al. 2012). The famous event was recorded in 1883 when the eruption of Krakatau triggered a catastrophic global tsunami that caused almost 36,000 fatalities (Self and Rampino

1981). Around 135 years later, a flank collapsed of Anak Krakatau triggered a tsunami in Sunda Strait on 22 December 2018 that caused hundreds of lives lost. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

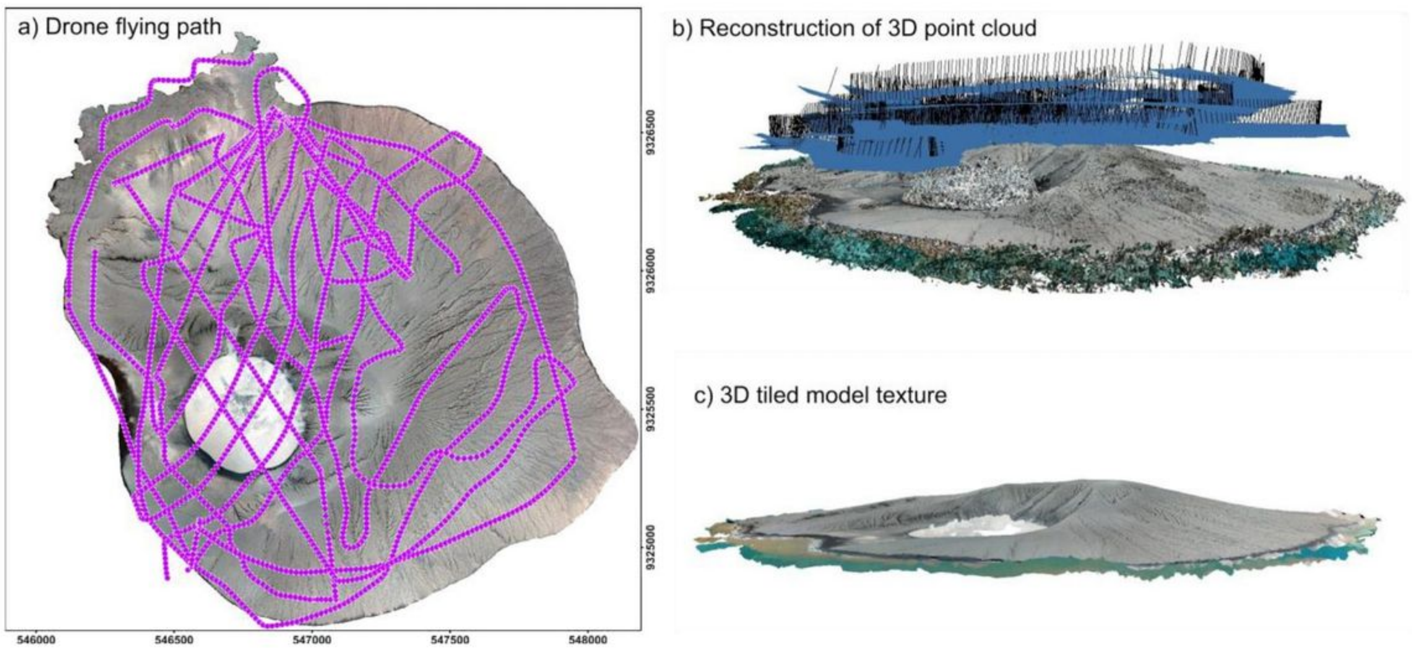

Figure 2

a) coverage area of aerial images taken by the drone. The purple dots indicate the location of aerial drone image data sampling. b) By using structure from motion algorithm, we can derive 3D dense point cloud that can be further processed to obtain c) 3D tiled model texture. This model can be exported as Digital Elevation Model and orthomosaic data for morphological and structural analysis. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

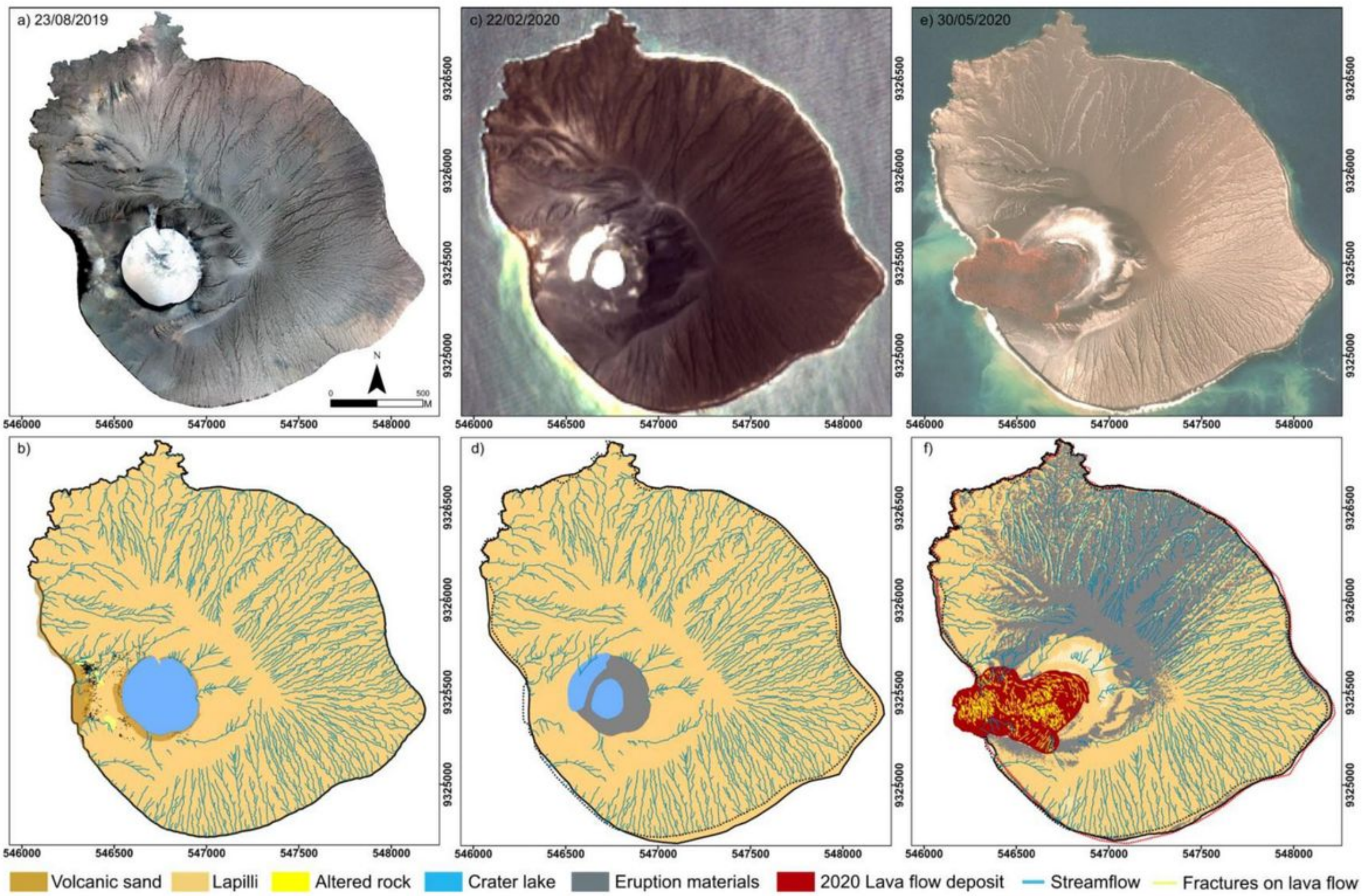

Figure 3

Morphological changes of Anak Krakatau between a-b) August 2019, c-d) February and e-f) May 2020. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

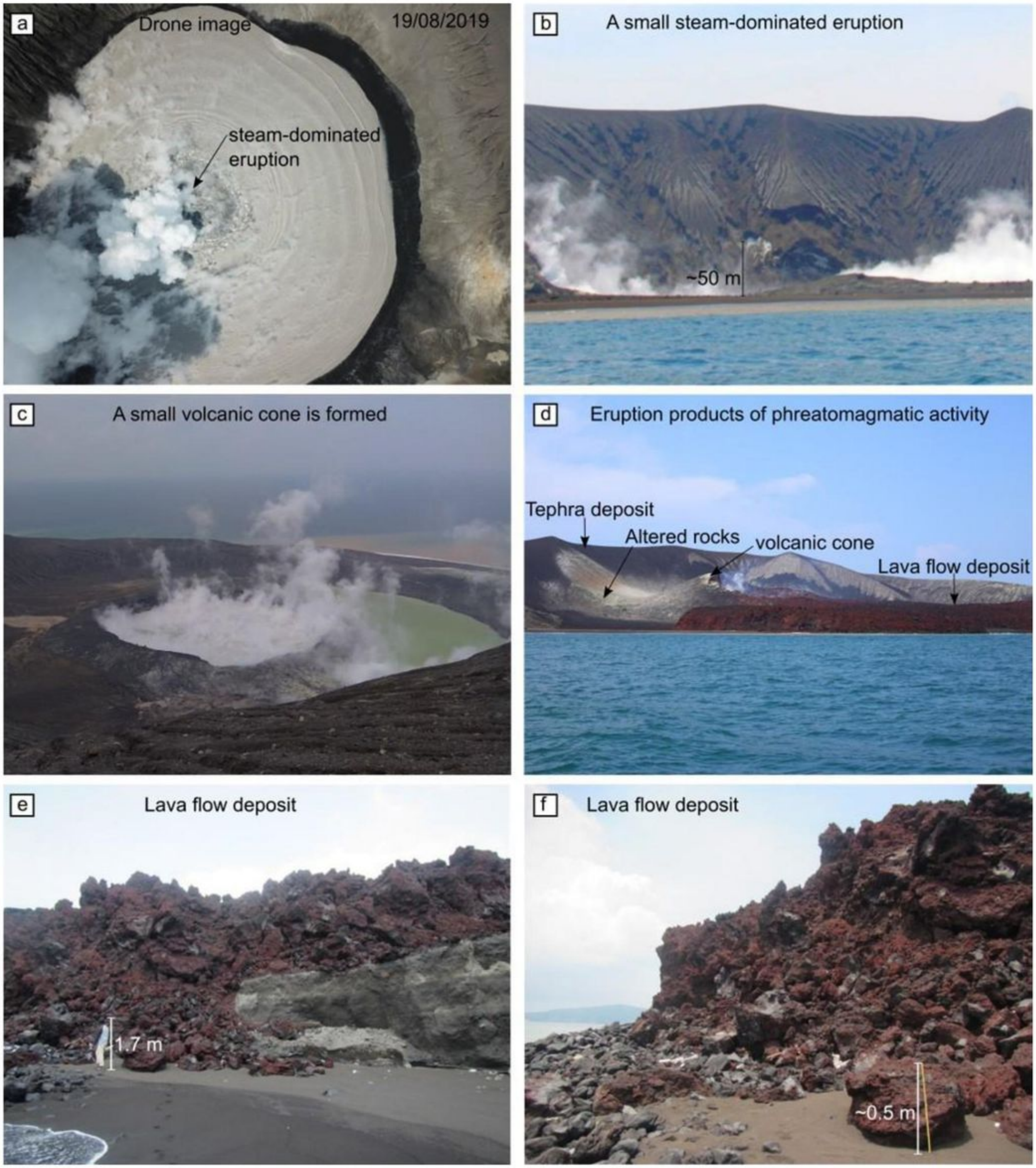

Figure 4

a-b) A hydrothermal eruption that occurred at Anak Krakatau produced steam dominated eruption in 2019. b) Series of hydrothermal and/or phreatomagmatic eruptions that occurred between January and February 2020 has formed a small volcanic cone at the crater lake of Anak Krakatau. d) Large phreatomagmatic and effusive eruptions ejected volcanic tephra and lava flow deposit at the west flank area of Anak Krakatau. e-f) Close observation of lava flow deposit shows surface blocky and some large fragments of a lava flow during emplacement.

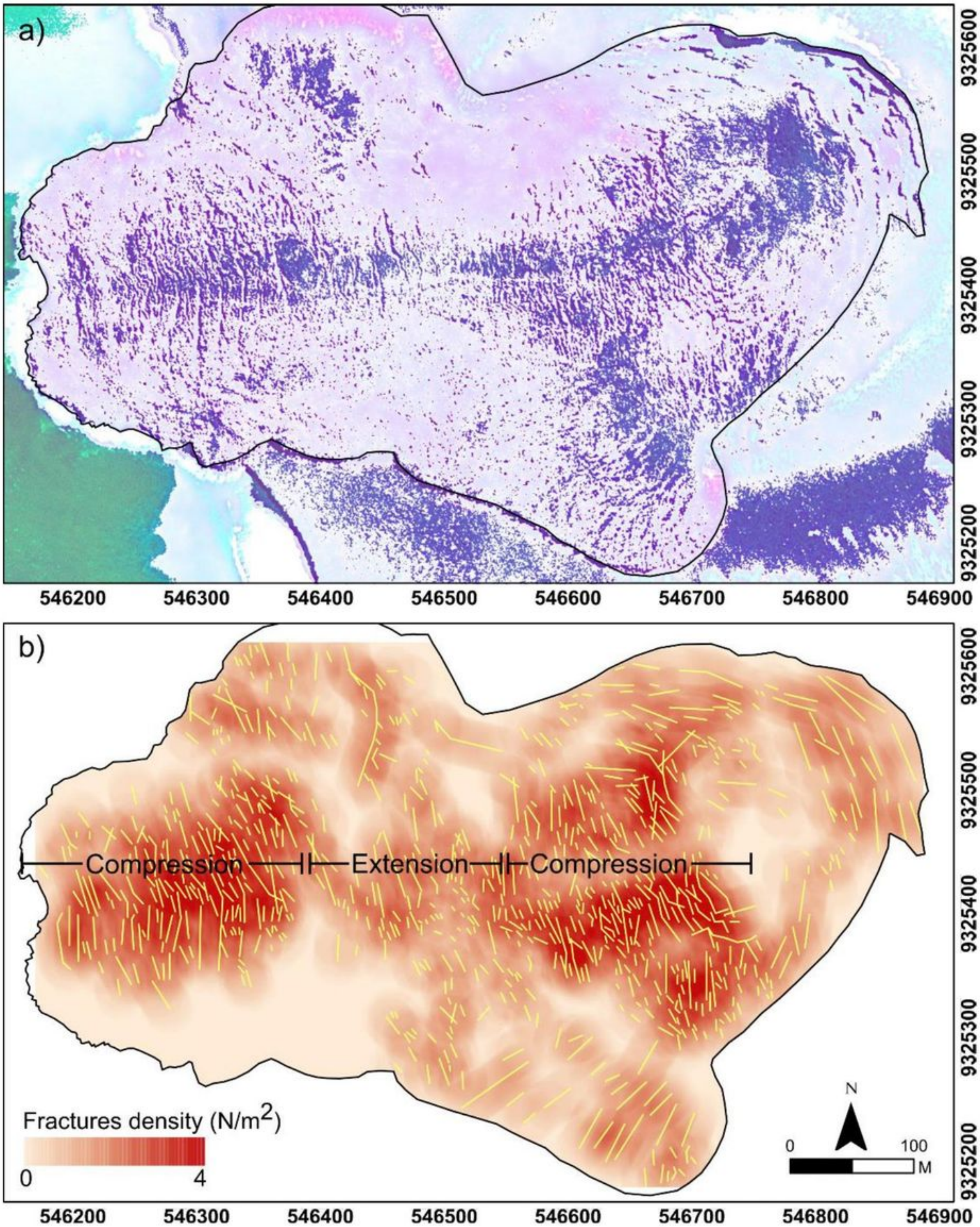

Figure 5

a) A combination of 4, 3, 1 on RGB bands of Pleiades satellite image provides detailed structures of the lava flow at Anak Krakatau. b) structural analysis shows some areas that undergo compression – extension – compression at lava flow of Anak Krakatau. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

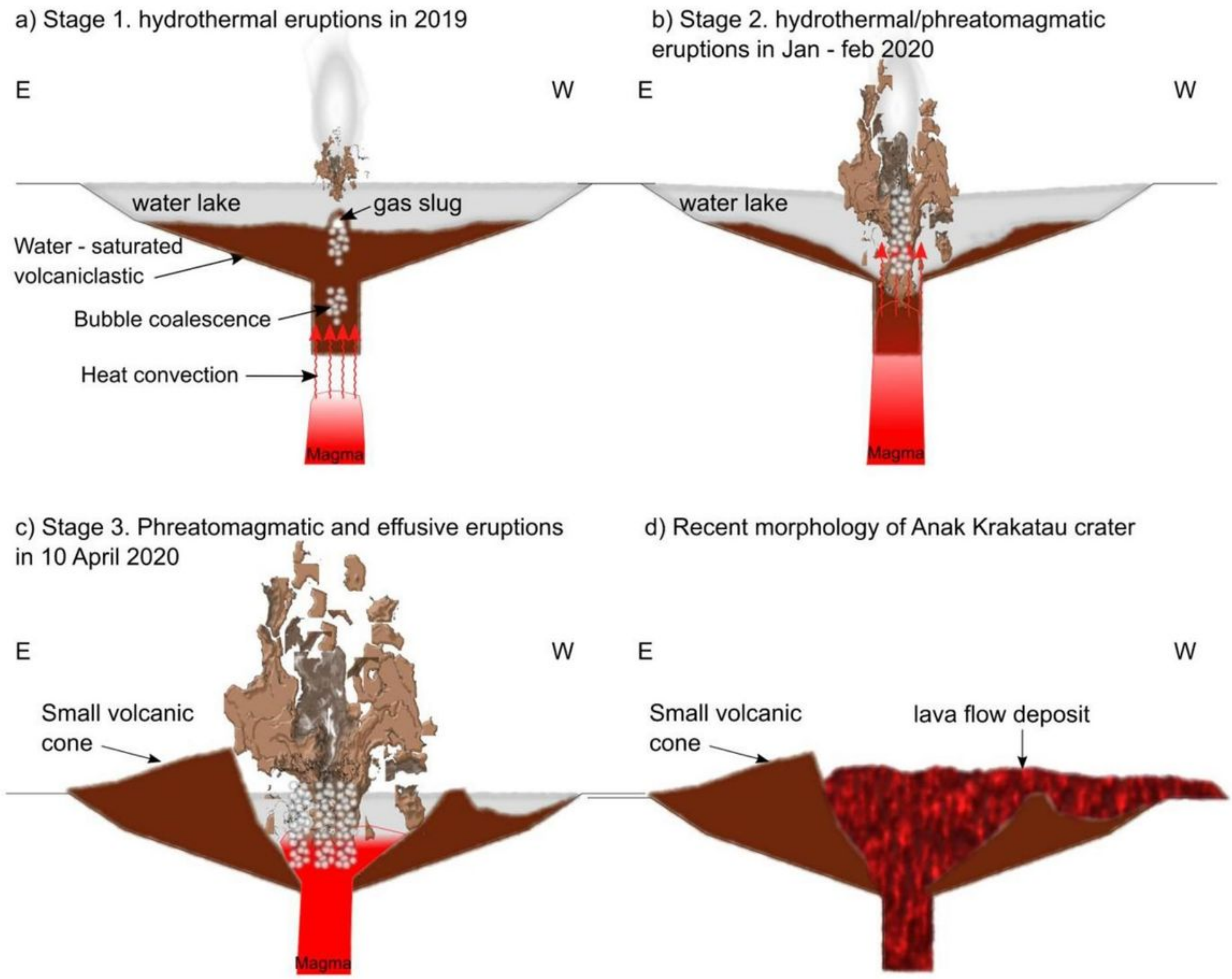

Figure 6

Morphological changes of the Anak Krakatau edifice that occurred between 2019 and 2020 are strongly controlled by hydrovolcanism activities that consist of a) hydrothermal eruptions in 2019, b) hydrothermal and/or phreatomagmatic eruptions between January and February 2020, c) Large phreatomagmatic and effusive eruptions on 10 April 2020. d) The last event produced a massive lava flow deposit that significantly reconstructs the west edifice of Anak Krakatau.

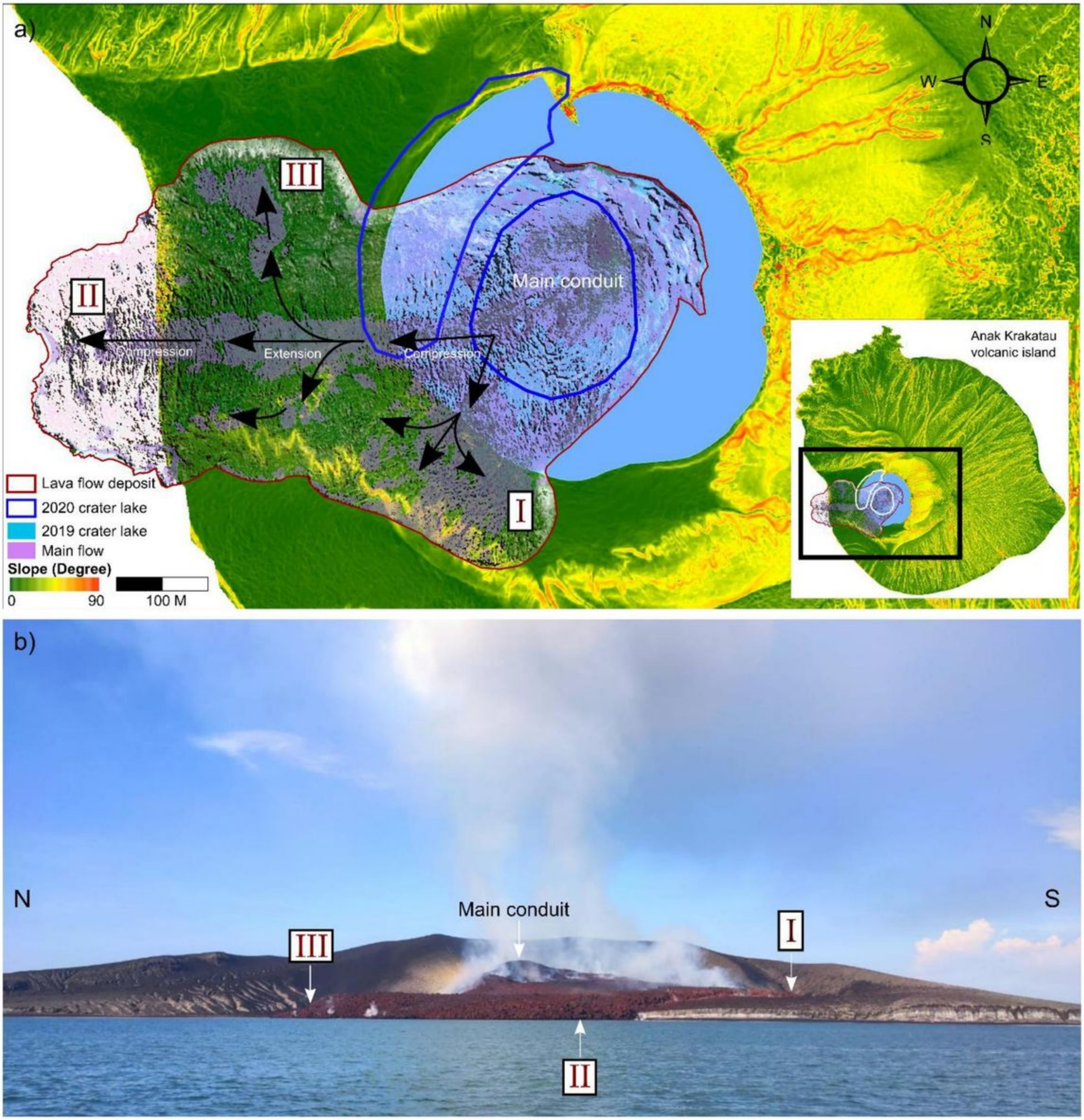

Figure 7

The emplacement of a lava flow is strongly controlled by the basal surface. a) Overlay of lava flow deposit on slope map suggests that most of the lava flow has deposited at a low slope topography profile. b) The lava flow has three lava levees, as observed by field photographs and satellite imageries. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.