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Supplementary information for

Reconstructing the Anak Krakatau flank collapse that caused the December 2018 Indonesian tsunami

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This supplementary information includes:

Figs. DR1 to DR3
Additional methods
Tables DR1
Captions for Movies DR1 to DR3

Other Supplementary Information for this manuscript include the following:

Movies DR1 to DR3: 2019343_Movies DR1-DR3.zip

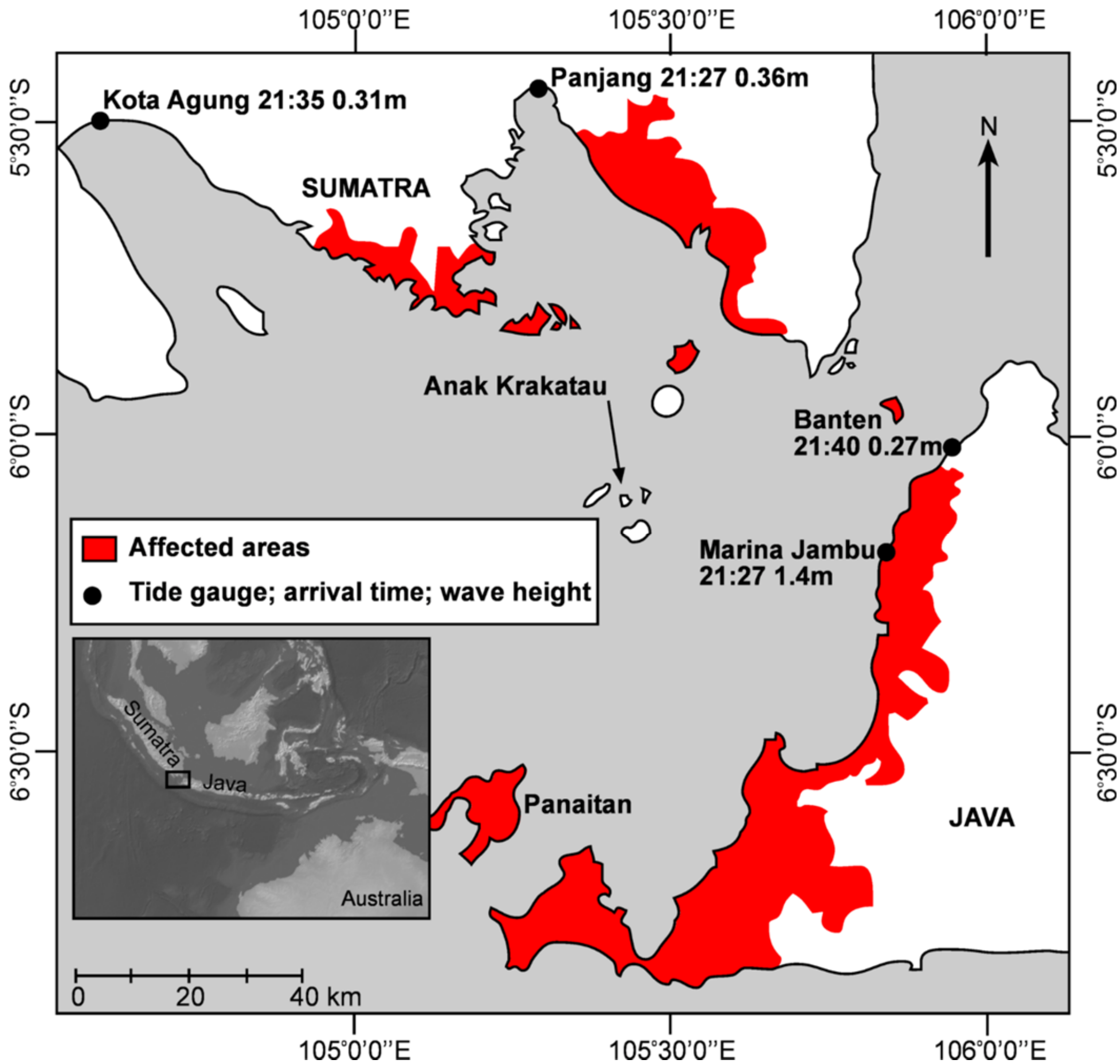

Fig. DR1.

Location map of Anak Krakatau showing tide gauges in the Sunda Strait with wave arrival times and wave heights of the 22 December 2018 tsunami. Red zones show coastal subdistricts affected by the tsunami, adapted from Tsunami selat sunda provinsi Banten dan Lampung map created by Badan Nasional Penanggulangan Bencana dated 28 December 2018. Wave heights and arrival times given by Pusat Vulkanologi dan Mitigasi Bencana Geologi in a press release dated 24 December 2018.

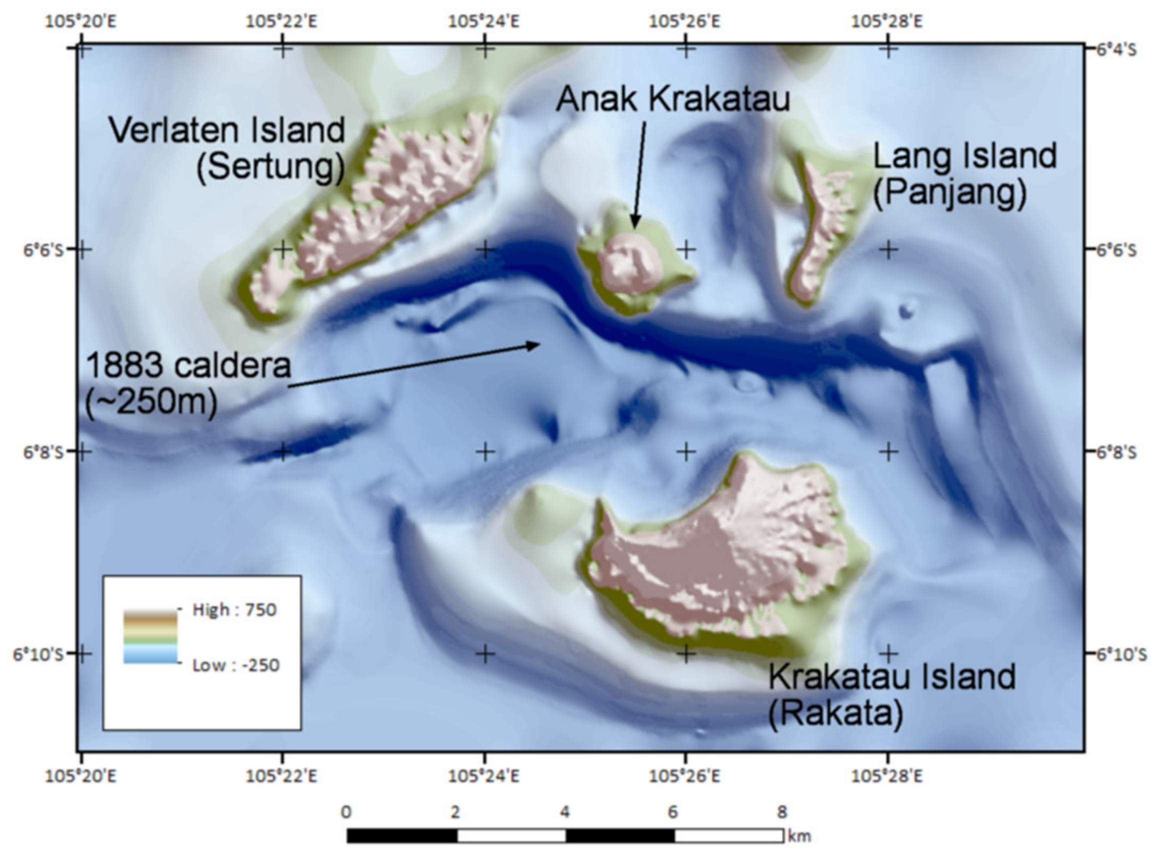

Fig. DR2

Bathymentric map of the 1883 caldera, redrawn from Deplus et al., 1995.

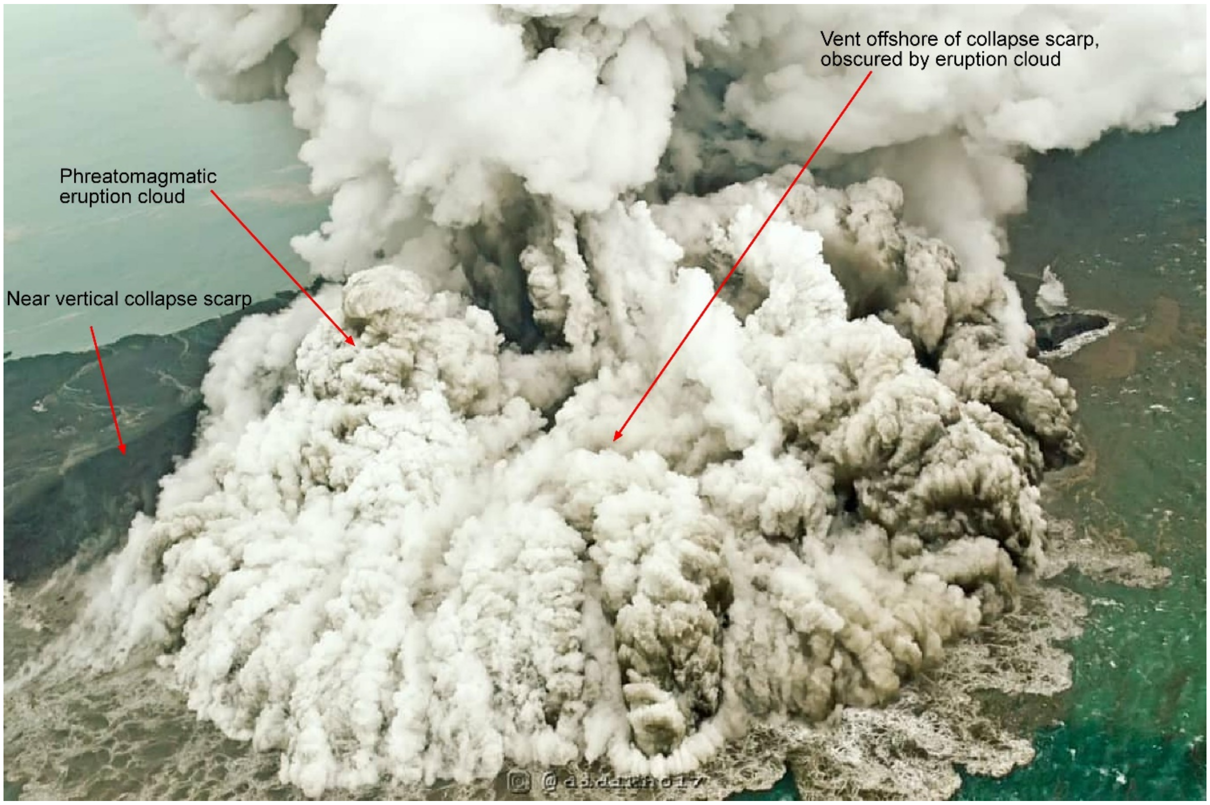

Fig. DR3.

Image of the phreatomagmatic eruption taken on the 23 December 17:06 WIB. The steep scarp (near vertical) created by the flank failure can be seen behind the eruption plume (revealed to the left of the plume). Photo direction towards ESE. Image credit, used with permission: Instagram @didikh017

Methods

Synthetic Aperture Radar Processing

We obtained Sentinel-1 "Interferometric Wide Swath" (IWS) SAR products from the Copernicus Open Access Hub in three viewing geometries: two descending orbits and one ascending orbit (Table DR1). Each SLC-format SAR product was converted to a "Sigma-0" backscatter coefficient image in slant-range geometry by applying the calibration and noise data annotated in the product metadata. We multi-looked (subsampled) the images to obtain approximately square pixels in radar geometry (4 range looks and 1 azimuth look).

A "master" image captured prior to the 22 December 2018 event was chosen for each of the three viewing geometries. Every other image within the three viewing geometry stacks (i.e. those not chosen as a "master") was then co-registered to its respective "master" image. Co-registration is the process of image alignment that involves measuring range and azimuth offsets between the two images via cross-correlation across a grid of sample windows covering the full image extents. A first-order polynomial transformation function is fitted (constant offset in range and azimuth directions) to the determined offsets and the image resampled to the radar-geometry of the "master" using a 2D Lanczos interpolation (of order 4). Every image was co-registered using an iterative procedure until the azimuth co-registration was better than 1/100 of a pixel. This high accuracy is particularly important if the Sentinel-1 IWS products are to be used for interferometry (not in this case). The result of this step is a stack of aligned radar-geometry images for each viewing geometry (Movie 1).

In a final step, the "master" image was used to derive a geocoding look-up table that can be used to transform the radar-geometry images to map view. This was done by first generating a simulated radar backscatter image from the 1-arc-second (~30 m) SRTM Digital Elevation Model (DEM) covering the geographic extent of the radar image footprints. This simulated radar image was then transformed to radar geometry using the orbit information annotated in the "master" image's product metadata. Subsequent co-registration between this image and the "master" image was performed to enable a refinement of the transformation parameters to be undertaken. Sentinel-1 image products usually only need a first-order polynomial transformation owing to the high quality of the provided orbit information. The Sentinel-1 image products we have used cover a much larger area than just the Krakatau caldera and include large portions of Java and/or Sumatra. Therefore the accuracy of the co-registration of the "master" images to the simulated radar image is not affected by the highly localised changes occurring at Anak Krakatau between image captures. A refined geocoding look-up table was then derived that provides a transformation to map view for every pixel in the radar-geometry image.

Finally, all radar-geometry images in each viewing geometry were orthorectified using the look-up table. A B-spline interpolation (of order 5) was used to perform the resampling.

Sentinel 2 Data

We obtained Sentinel 2A true colour images (TCI) collected on the 16th November 2018 from the Copernicus Open Access Hub.

DEM

We obtained a 0.27-arc-second resolution DEM from the Indonesian Geospatial Agency (Badan Informasi Geospasial). This DEM, covering the whole of Indonesia, was constructed from data from TerraSAR-X (from 2011 - 2013), InSAR (from 2000, 2004, 2008, and 2011) and ALOS-PALSAR (2007/2008) (pers. comm. Susilo Sarimun, Badan Informasi Geospasial, 7th February

2019). The heights given in the DEM are therefore relevant to an epoch sometime between 2000 and 2013. The DEM was converted to a triangulated irregular network (TIN), after resampling to a higher resolution grid.

Data availability

The Sentinel datasets analysed during the current study are available in the Copernicus Open Access Hub, https://scihub.copernicus.eu/. The DEM analysed is available from the Indonesian Geospatial Agency (Badan Informasi Geospasial) (http://tides.big.go.id/DEMNAS/#Info). Processed datasets generated during the current study are available from the corresponding author on reasonable request.

Table DR1.

Details of the Sentinel-1 SAR images used in this study. Elevation and Azimuth angles are for a looking vector towards the satellite originating at the summit cone of Anak Krakatau prior to the flank failure and tsunami. Italicised entries denote images captured before the 22 December 2018 event occurred.

Relative orbit	Pass	Satellite	Acquisition Date (UTC)	Time (UTC)	Days since previous	Elevation (deg)	Azimuth (deg)
171	*Ascending*	*S1A*	*7/12/2018*	*11:23:07*	-	*46.9*	*257.5*
171	*Ascending*	*S1A*	*19/12/2018*	*11:23:06*	*12*	*46.9*	*257.5*
171	Ascending	S1B	25/12/2018	11:22:35	6	46.9	257.5
171	Ascending	S1A	31/12/2018	11:23:06	6	46.9	257.5
171	Ascending	S1A	12/1/2019	11:23:05	12	46.9	257.5
47	*Descending*	*S1A*	*28/11/2018*	*22:33:45*	-	*45.1*	*102.6*
47	*Descending*	*S1A*	*10/12/2018*	*22:33:45*	*12*	*45.1*	*102.6*
47	Descending	S1A	22/12/2018	22:33:44	12	45.1	102.6
47	Descending	S1B	28/12/2018	22:33:06	6	45.1	102.6
47	Descending	S1A	3/1/2019	22:33:44	6	45.1	102.6
47	Descending	S1A	15/1/2019	22:33:44	12	45.1	102.6
120	*Descending*	*S1A*	*3/12/2018*	*22:41:39*	-	*58.6*	*102.3*
120	*Descending*	*S1A*	*15/12/2018*	*22:41:39*	*12*	*58.6*	*102.3*
120	Descending	S1A	27/12/2018	22:41:38	12	58.6	102.3
120	Descending	S1B	2/1/2019	22:41:04	6	58.6	102.3
120	Descending	S1A	8/1/2019	22:41:38	6	58.6	102.3
120	Descending	S1A	20/1/2019	22:41:38	12	58.6	102.3

Movie DR1.

Animated compilation of Sentinel-1 SAR backscatter images in the native radar viewing geometry (T120D). Annotated labels give the viewing geometry (relative orbit and pass direction) and the image capture date (UTC). Image x-axis is the range direction and y-axis is the azimuth, or along-track direction of the radar viewing geometry. Details of the three viewing geometries are given in Table DR1.

Movie DR2.

Animated compilation of Sentinel-1 SAR backscatter images in the native radar viewing geometry (T171A). Annotated labels give the viewing geometry (relative orbit and pass direction) and the image capture date (UTC). Image x-axis is the range direction and y-axis is the azimuth, or along-track direction of the radar viewing geometry. Details of the three viewing geometries are given in Table DR1.

Movie DR3.

Animated compilation of Sentinel-1 SAR backscatter images in the native radar viewing geometry (T047D). Annotated labels give the viewing geometry (relative orbit and pass direction) and the image capture date (UTC). Image x-axis is the range direction and y-axis is the azimuth, or along-track direction of the radar viewing geometry. Details of the three viewing geometries are given in Table DR1.