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The December 2018 volcano-triggered tsunami in Krakatau complex (Sunda Strait, Indonesia)

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About

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Scientific Mission

Of the National and Kapodistrian University of Athens, Faculty of Geology and Geoenvironment, Department of Dynamic Tectonic Applied Geology

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VOLCANO-TRIGGERED TSUNAMI GENERATED IN THE SUNDA STRAIT (INDONESIA)

Tsunamis are caused either by various natural processes comprising earthquakes, surface or submarine landslides, rock avalanches, volcanic eruptions, meteorological disturbances, underwater gas emission and asteroid impacts or man-made processes including submarine nuclear bomb testing. According to their generation mechanism, tsunamis are classified as (a) seismic tsunamis produced by earthquakes resulting in coseismic fault displacement of the sea bed and (b) non-seismic tsunamis induced without direct involvement of an earthquake.

Tsunamis are further classified into aseismic tsunamis due to landslides, volcanic activity or other causes without any seismic triggering and pseudoseismic tsunamis due to landslides or volcano collapse due to earthquake acting only as a triggering factor and without the involvement of coseismic fault displacement (Papadopoulos, 1993, 2016).

A non-seismic tsunami was generated occurred on December 22 at 21:27 near the Anak Krakatau volcano complex, located in the Sunda Strait between the Western Java and the Southern

Sumatra, causing until now 430 fatalities, 159 missing, about 1459 injured people and 21991 displaced people.

This is not the first time that a tsunami struck the Sunda Strait. Based on tsunami catalogues, it was hit by tsunamis triggered by earthquakes in 1722, 1852 and 1958, by eruptions or other activity of Krakatau complex in 416, 1883 and 1928 and other unknown causes in 1851, 1883 and 1889.

The December 2018 volcano-triggered tsunami is attributed to the collapse of the flank of the Anak Krakatau volcano, especially in its southern and southwestern sectors. This eruption resulted in the destruction of the local seismographic equipment though a nearby seismographic station detecting continuous tremors.

The tsunami arrived at the coastal areas of western Java and southern Sumatra in 24 minutes after the eruption of the volcano that occurred at 21:03 of December 22.



VOLCANO-TRIGGERED TSUNAMI GENERATED IN THE SUNDA STRAIT (INDONESIA)

Due to the fact that (a) there was either no generation of a seismic event or no recording of a seismic event due to technical difficulties and (b) the Indonesian Tsunami Early Warning System has been not operating since 2012 due to lack of funding, there was no warning about the upcoming tsunami. The volcano-triggered tsunami devastated the coastal areas of western Java and southern Sumatra, and in particular Banten Province (Java) and Lampung Province (Sumatra), Indonesia.

Based on observations of tidal stations, the arrival time and height of the first wave were recorded as follows:

- at Marina Jambu Station (Bulakan Village, Cinangka District, Serang District, Banten) arrived at 21:27 WIB, with a height of 1.4 m.
- at the Banten Station (Ciwandan Port, Cilegon City, Banten) arrives at 21:40 WIB, with a height of 0.27 m.
- at Kota Agung Station (Kota Agung Subdistrict, Tanggamus Regency, Lampung) arrived at 21:35 WIB, with a height of 0.31 m.
- at Stasiun Panjang (Panjang Port, Bandar Lampung City, Lampung) arrived at 21:27 WIB, with an altitude of 0.36 m.

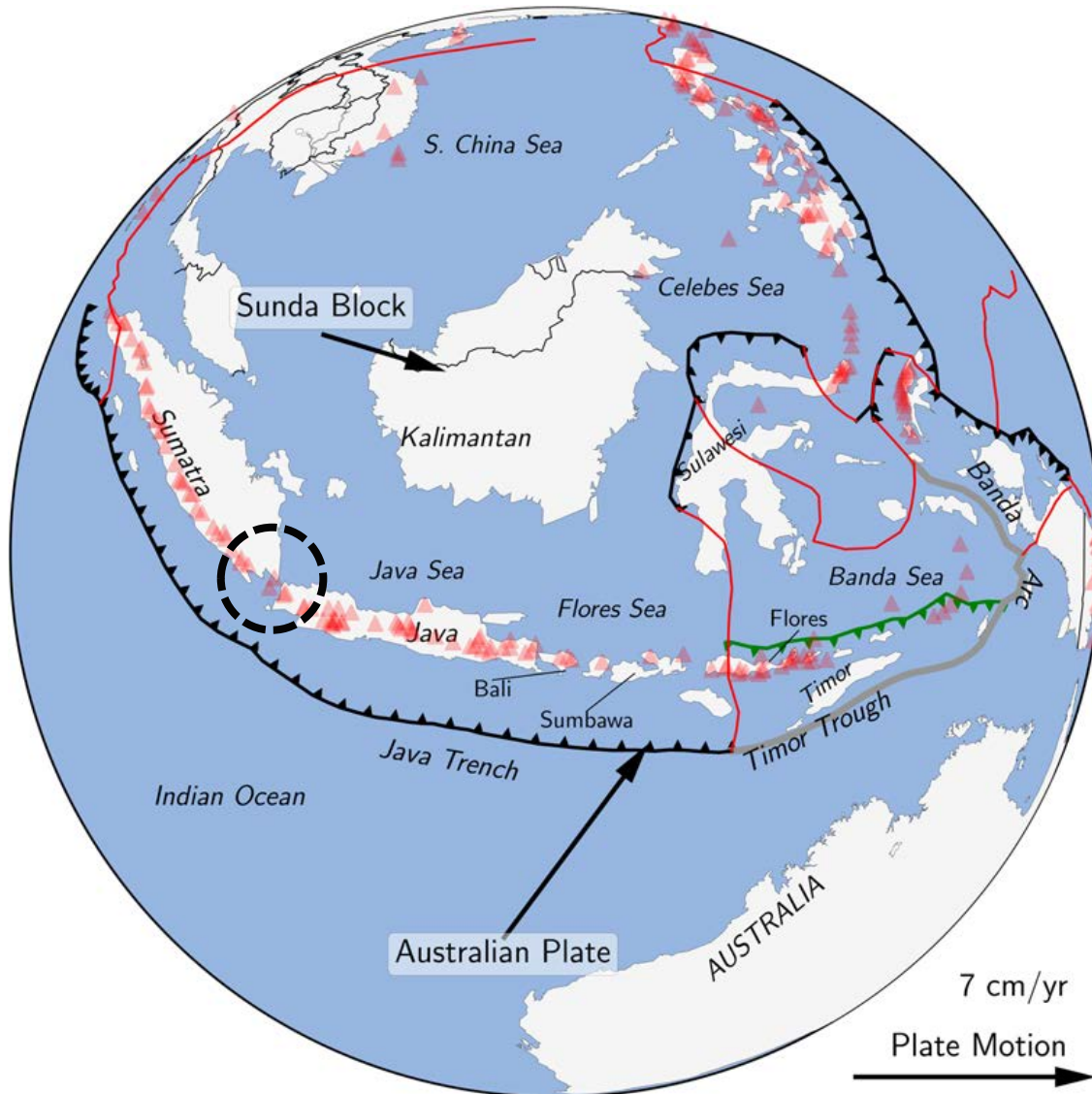
The scientific team of the National and Kapodistrian University of Athens visited the worst tsunami-affected area shortly after the disaster aiming to investigate the impact of the volcano-triggered tsunami on the natural and built coastal environment.

All type of tsunamis have disastrous impact on the natural and built environment of the affected coastal areas.

As regards the impact on the natural environment, coastal geomorphological changes, soil erosion, tsunami sediment deposition and boulder emplacement were caused by the December 2018 volcano-triggered tsunami along the coasts of the Sunda Strait. Soil erosion along the affected beaches was induced due the tsunami. Waves locally removed beach sand about 1 m vertically and 20 to 30 meters wide and deposited it further inland. Moreover, boulders were either detached from and emplaced on shallower parts of the sea bed close to the affected beaches or displaced for a small distance.



ACTIVE TECTONICS OF THE INDONESIAN REGION

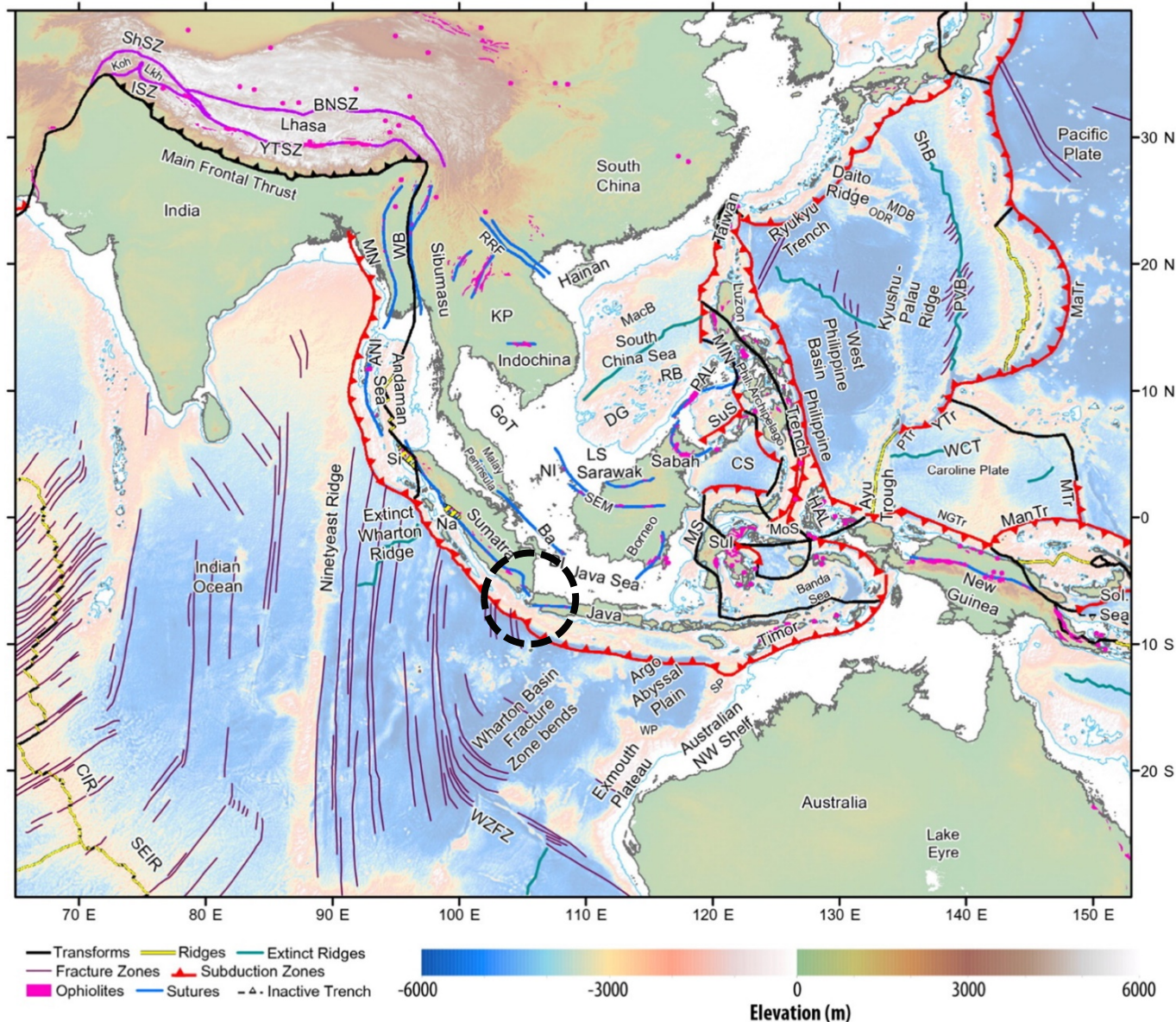


Active tectonics of the Indonesian Region. Major plate boundaries are indicated: subduction zones and back-arc thrusts by the black and green 'toothed' curves, respectively; plate boundaries with uncertain relative movement by grey curves; and other transform boundaries by red curves. Also indicated are Holocene volcanoes (red triangles) and the absolute motion of the Australian Plate and the Sunda Arc.

From Cummins (2017),
Geological Society, London, Special Publications,
441

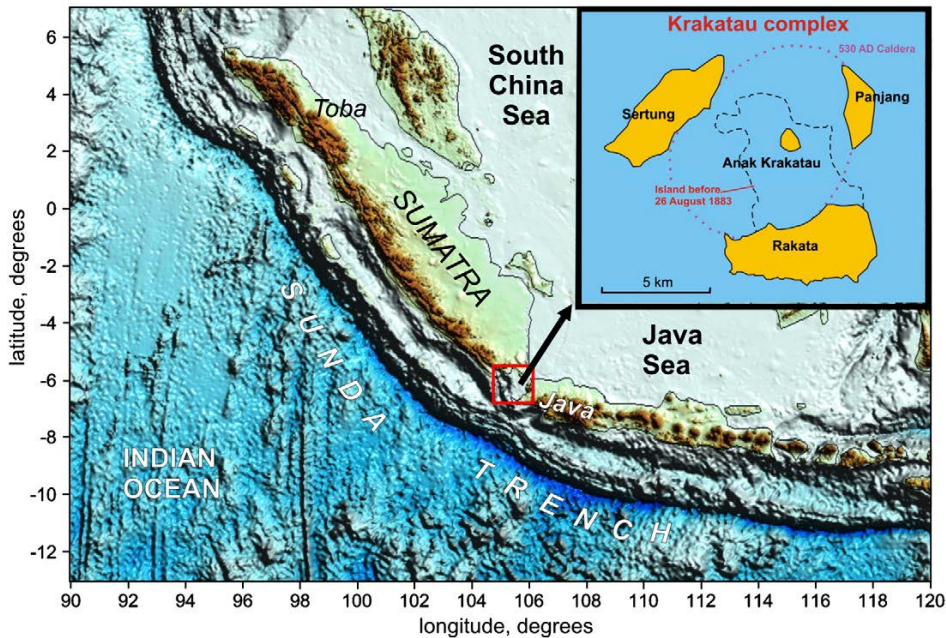


REGIONAL TECTONIC SETTING OF SOUTHERN EURASIA, SOUTHEAST ASIA AND NEW GUINEA



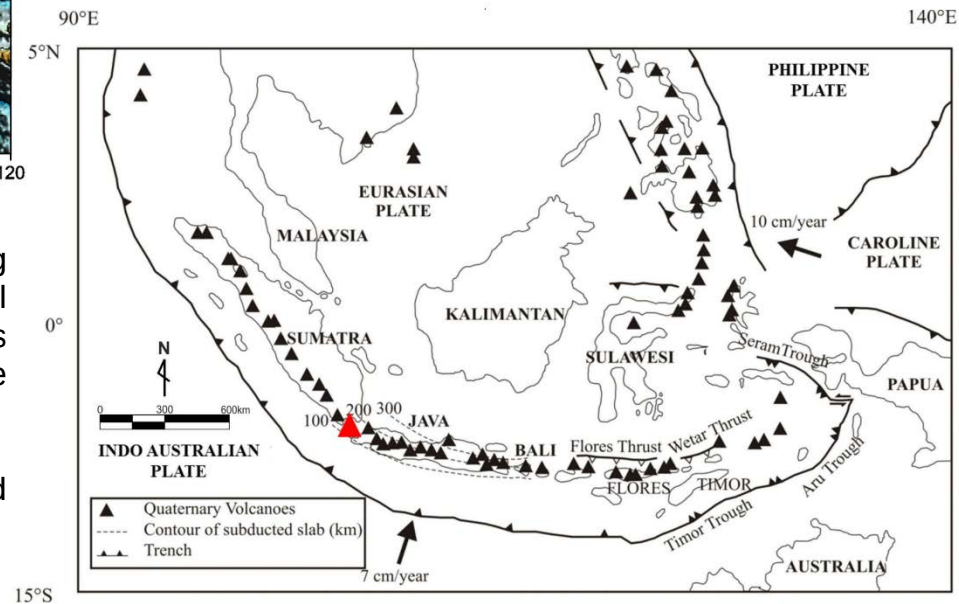


THE KRAKATAU COMPLEX IN SUNDA STRAIT



Topography and bathymetry of the Sunda Arc and surrounding areas. Red rectangle indicates the Krakatau complex. Coastal line of Krakatau Island before the catastrophic 1883 eruptions is indicated by black dashed line. Caldera corresponding to the ~530 AD eruption is marked by red dotted line.

From *Jaxybulatov et al. (2011)*, Journal of Volcanology and Geothermal Research

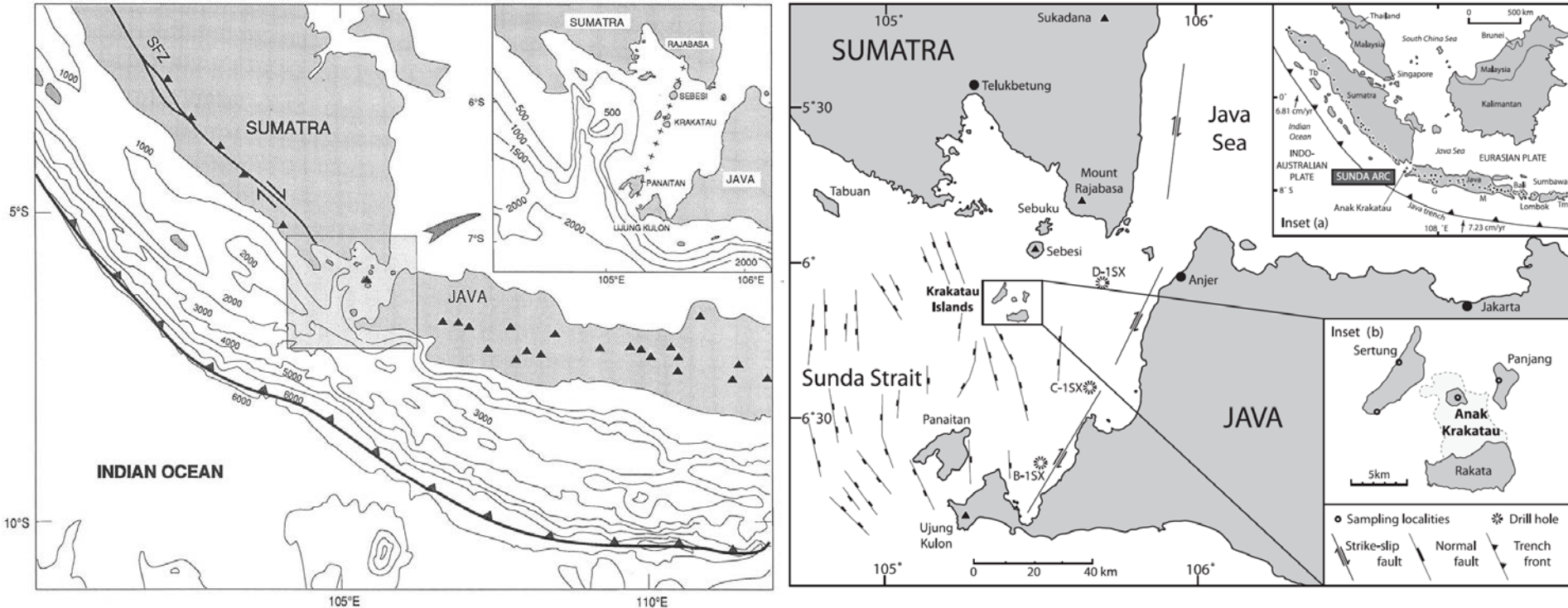


Tectonic map of Indonesia showing the interaction of 3 major plates. Red triangle depicts Krakatau volcanic complex.

From *Abdurachman et al. (2018)*, Geosciences



GEODYNAMIC SETTING AND BATHYMETRY OF THE KRAKATAU VOLCANIC COMPLEX



Geodynamical context of the Krakatau volcanic complex. (a) Heavy solid line with black triangles: trench axis for the subduction of the Indo-Australian plate beneath the South-East Asian plate. Light solid lines: isobaths in meters. Black triangles: volcanoes along the volcanic arc related to the subduction. SFZ: Sumatra Fault Zone. (b) Detailed view of the Sunda Strait with location of the Krakatau complex.

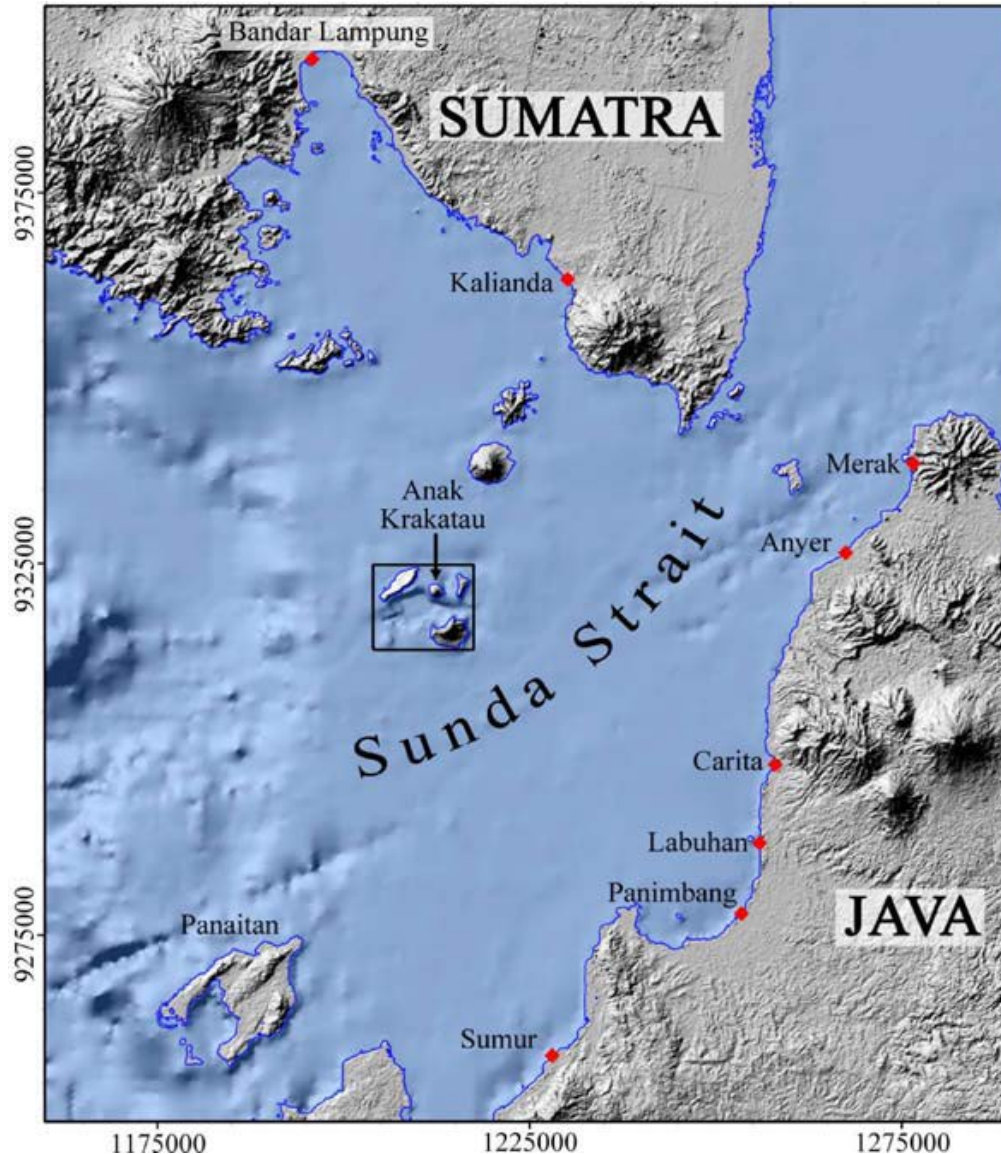
From *Deplus et al. (1995)*,
Journal of Volcanology and Geothermal Research

Tectonic setting and location map of the Sunda Strait and of the wider Sunda Arc area (inset a) with the current configuration of the Krakatau volcanic complex (inset b). Faults from Schlüter et al. (2002) and Susilohadi et al. (2009). Tb: Toba; G: Galunggung; M: Merapi; Tm: Tambora.

From *Gardner et al., (2013)*
Journal of Petrology



THE KRAKATAU COMPLEX IN SUNDA STRAIT

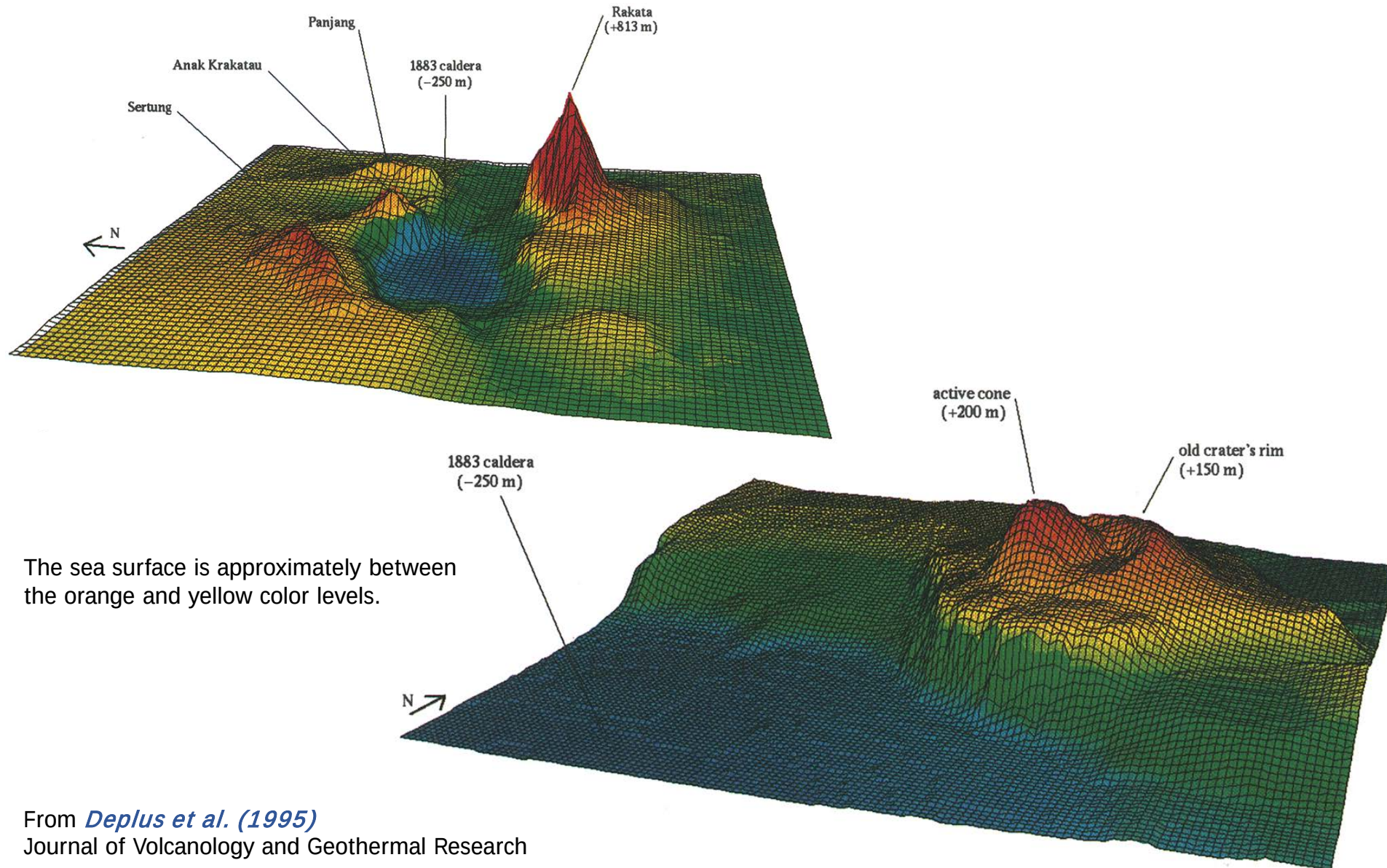


Shaded relief representation of the DEM (100 m resolution) of Sunda Strait, based on ASTER topography, GEBCO bathymetry and a digitization of the bathymetric map of Krakatau from Deplus et al. (1995). The main coastal cities or important infrastructures around the Sunda Strait are indicated by red diamonds.

From *Giachetti et al. (2012)*,
Geological Society, London, Special Publications, 361

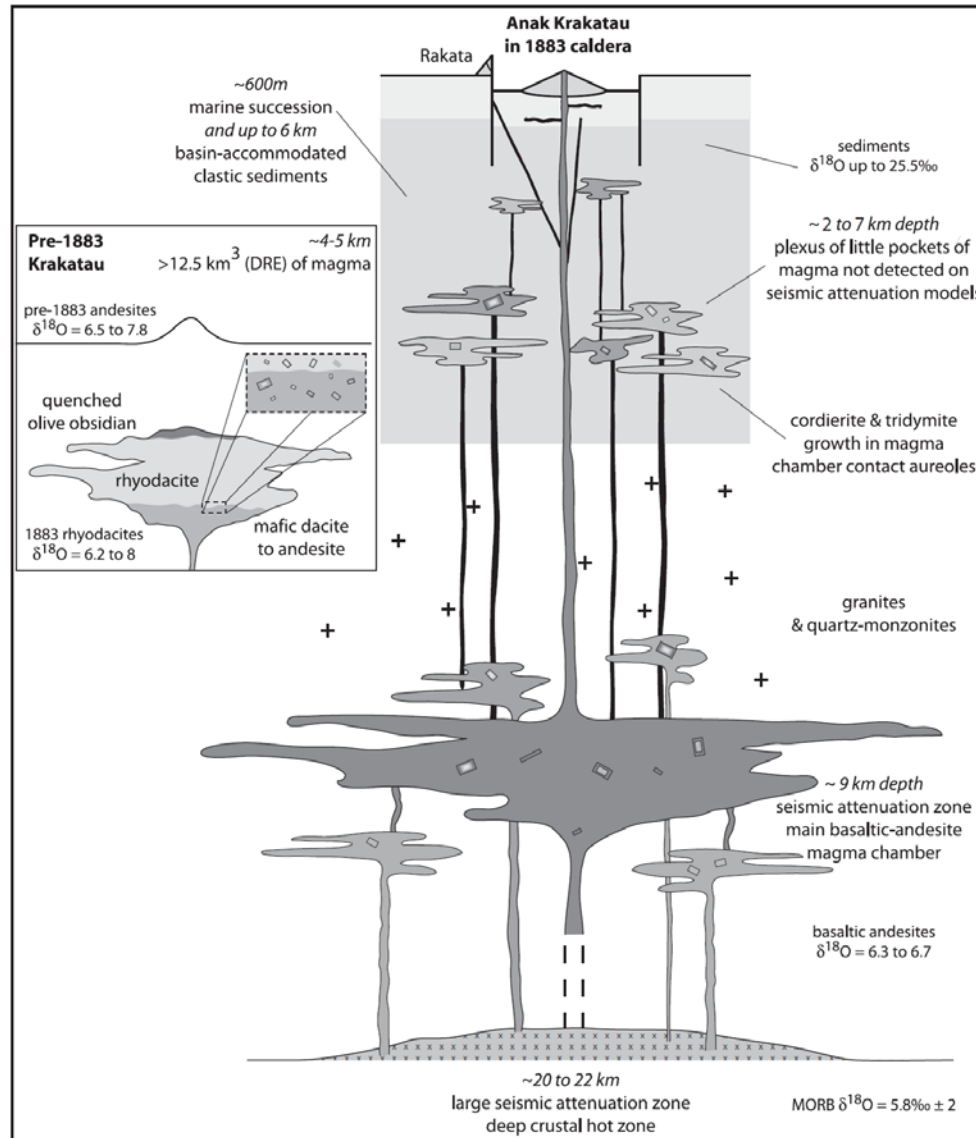


THREE DIMENSIONAL NUMERICAL MODEL OF KRAKATAU VOLCANIC COMPLEX





THE MAGMA PLUMBING SYSTEM FOR THE KRAKATAU VOLCANIC COMPLEX

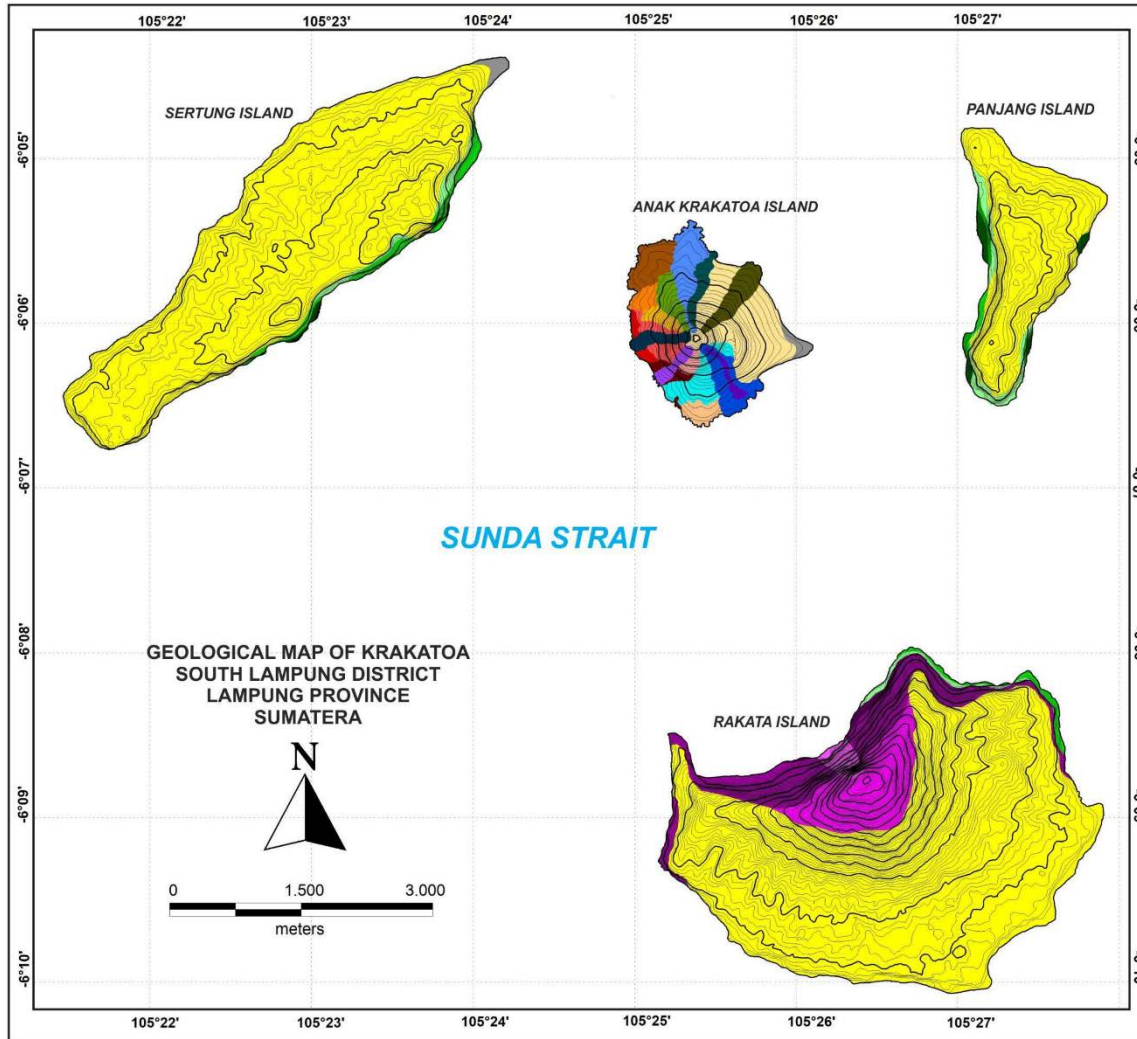


Schematic illustration of the magma plumbing system for the Krakatau volcanic complex (not to scale). Geophysical evidence refutes the existence of a large-volume shallow magma chamber beneath Anak Krakatau at present and current Anak Krakatau activity is probably sourced from a plexus of small and partly crystalline, semi-independently evolving pockets of magma that are not always clearly detectable by geophysical means.

From *Gardner et al. (2013)*
Journal of Petrology



GEOLOGICAL STRUCTURE OF THE KRAKATAU COMPLEX

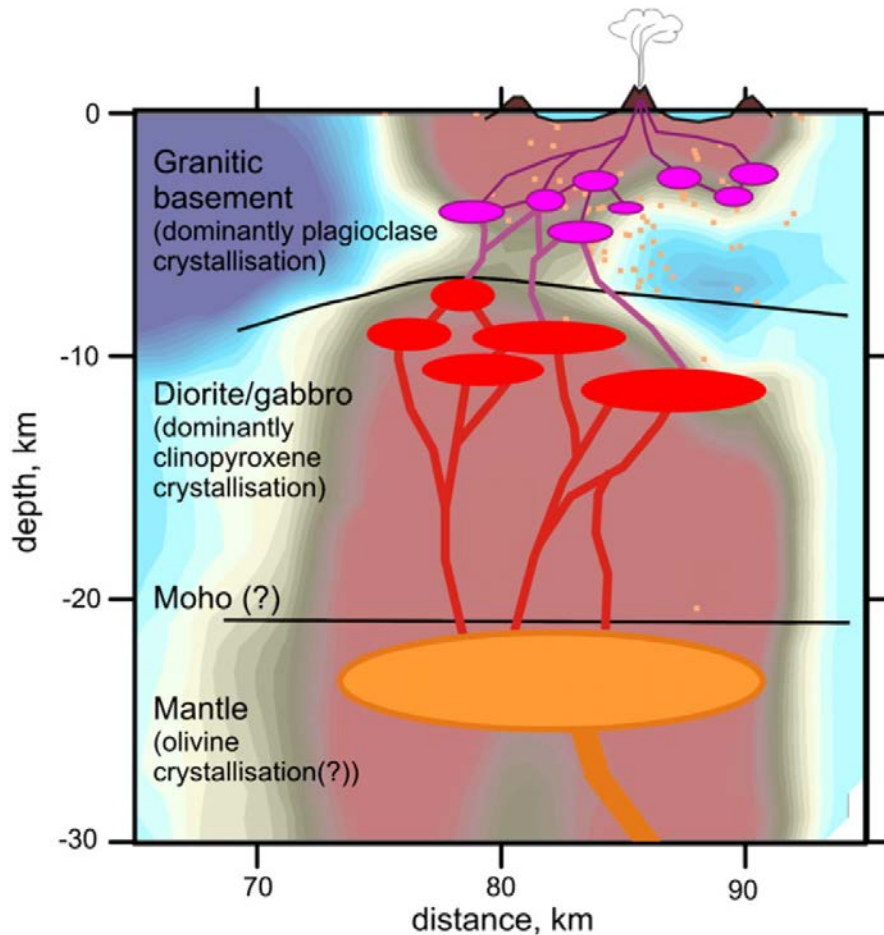


Time Scale	Eruptive Center	Volcanic Product			Alluvial
		Lava	Pyroclastic		
			Flow	Fall	
2017	EAST ANAK KRAKATOA				
2014					
2012					
2010					
2008					
2007					
2002		★			
1999					
1998					
1997					
1996					
1995					
1994					
1993					
1992					
1988					
1984					
1981		★			
1979					
1975					
1973					
1972					
1960	WEST ANAK KRAKATOA				
1959					
1953					
1952					
1940					
1936					
1935					
1934					
1927					
1883		★			
1200	PARBUWATAN				
	DANAN				
	RAKATA				
					
416					
					

From *Abdurrachman et al. (2018)*
Geosciences

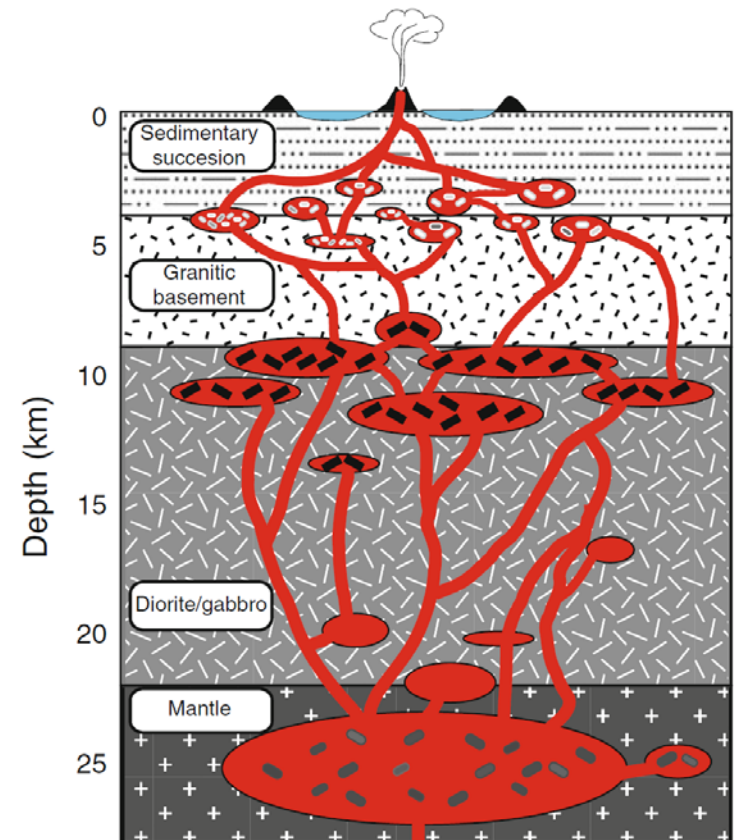


THE KRAKATAU COMPLEX IN SUNDA STRAIT



Interpretation cartoon for the distribution of magma chambers beneath the Krakatau complex. Location of the caldera and the active Anak Krakatau is schematically shown.

From *Jaxybulatov et al. (2011)*
Journal of Volcanology and Geothermal Research

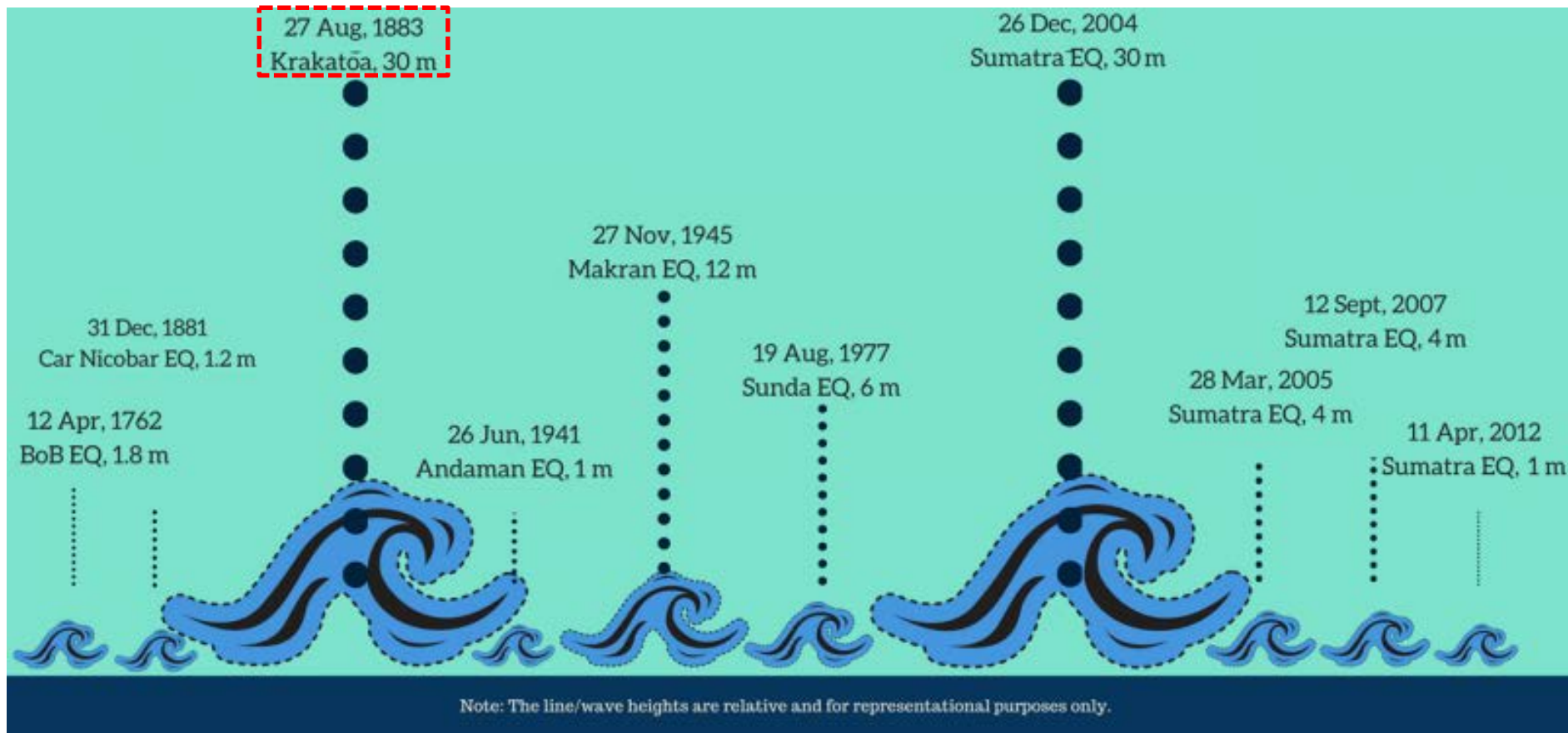


Schematic illustration of the magma plumbing system at Anak Krakatau based on thermobarometric and geophysical data

From *Dahren et al. (2012)*
Contributions to Mineralogy and Petrology



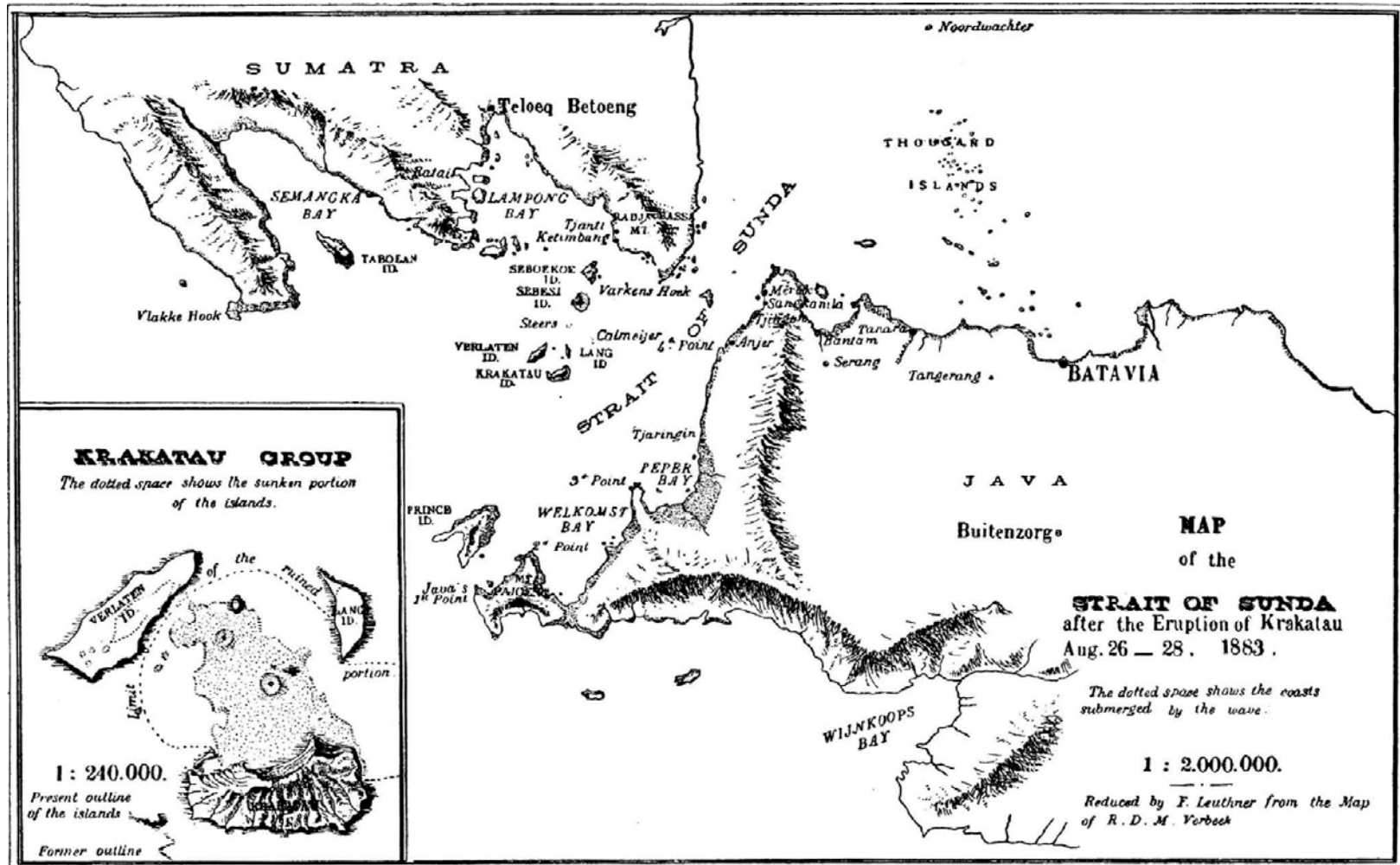
HISTORICAL EARTHQUAKE- AND TSUNAMI- TRIGGERED TSUNAMIS IN THE INDIAN OCEAN



Volcano-triggered tsunamis are rare not only in Indian Ocean but throughout the world



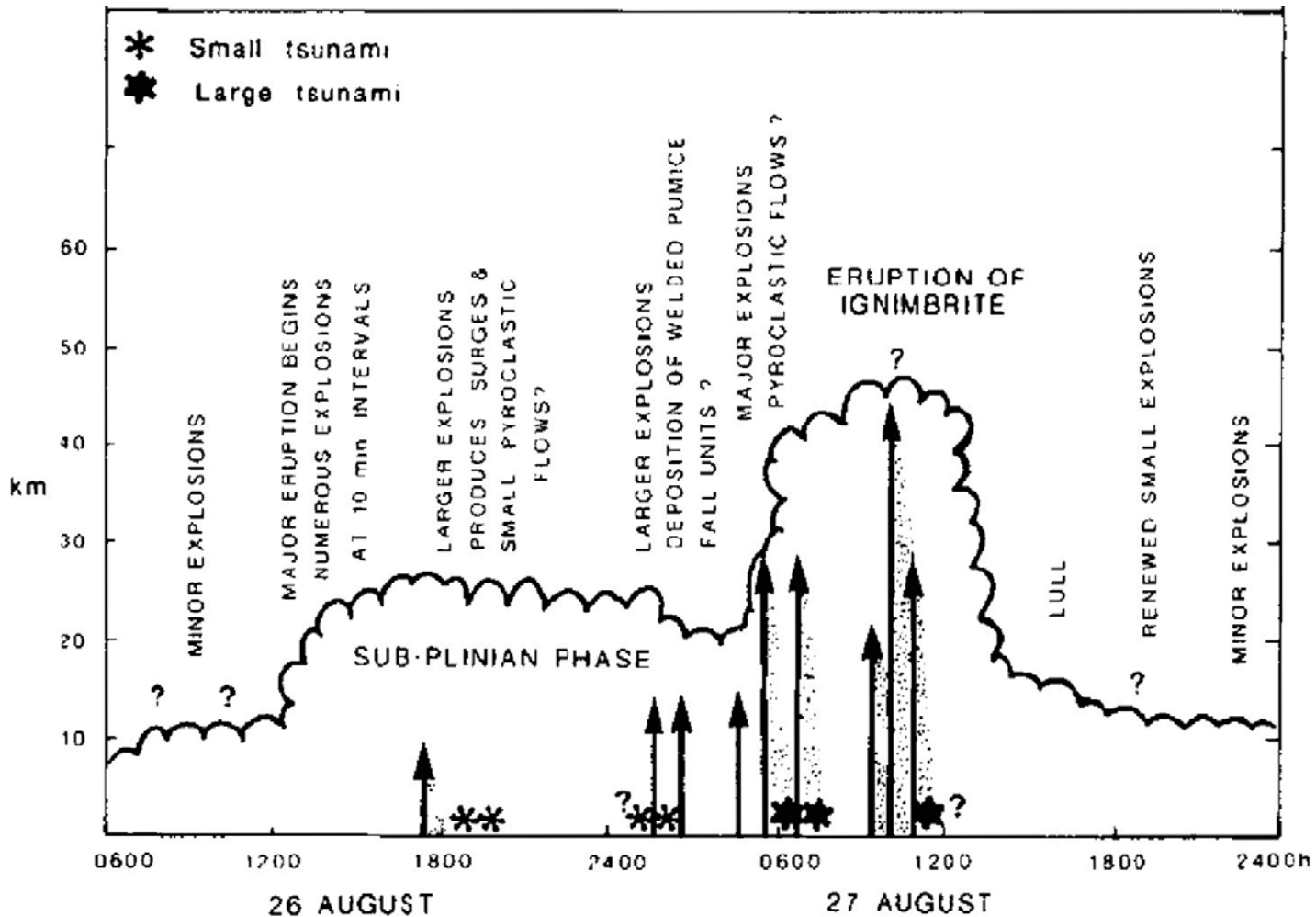
THE 1883 KRAKATAU ERUPTION DETAILED BATHYMETRIC MAP OF THE 1883 CALDERA



Map of the Sunda Strait after the eruption of Krakatoa (Hurlbut and Verbeek, 1887)
From *Schaller et al. (2009)*, Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich (2009)



THE 1883 KRAKATAU ERUPTION CHRONOLOGY OF THE KRAKATAU ERUPTION

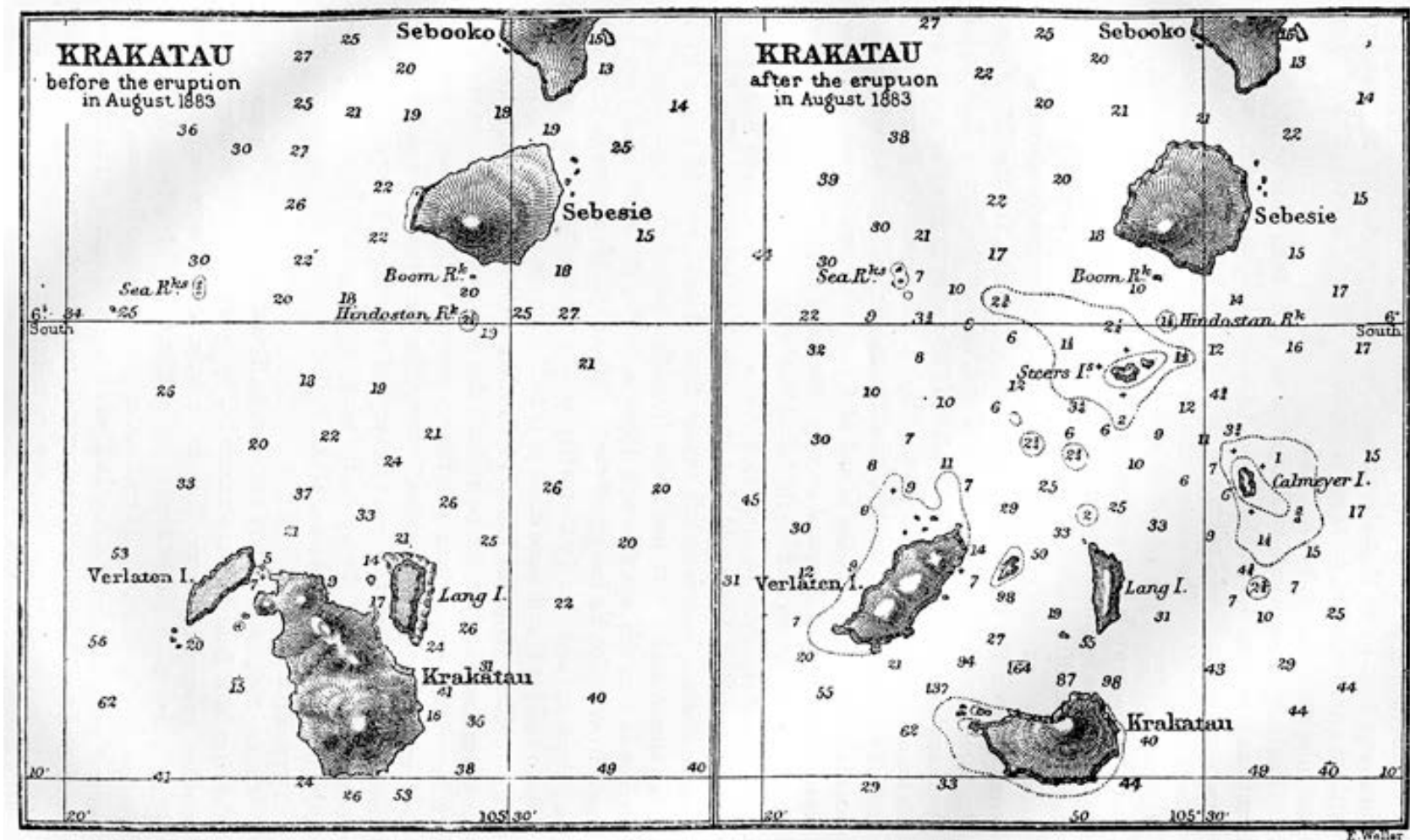


Chronology of the Krakatoa eruption during its most active phase on 26 and 27 August 1883. In the beginning the eruption was plinian, later Ignimbrit-forming. The thin (bold) asterisks stand for small (large) tsunami events (Self and Rampino, 1981).

From [Schaller et al. \(2009\)](#), Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich (2009)



THE EVOLUTION OF KRAKATAU VOLCANIC COMPLEX BEFORE AND AFTER THE 1883 ERUPTION

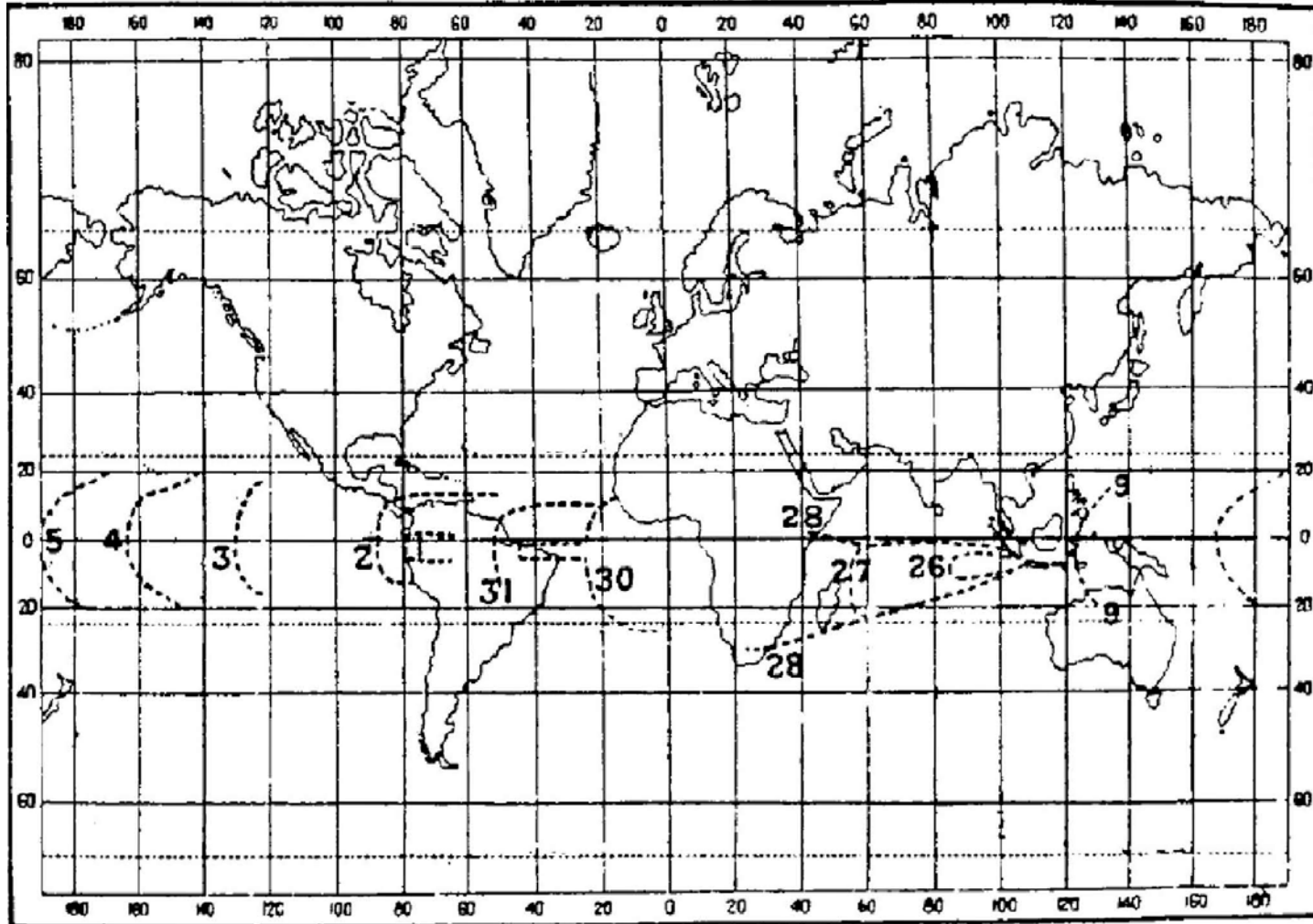


Krakatoa – before and after: notice how much of the island of Rakata (labelled Krakatau) has disappeared in the eruption and the large shoals of pumice that formed new islands northwest of Krakatau.

From *Proceedings of the Royal Geographical Society*



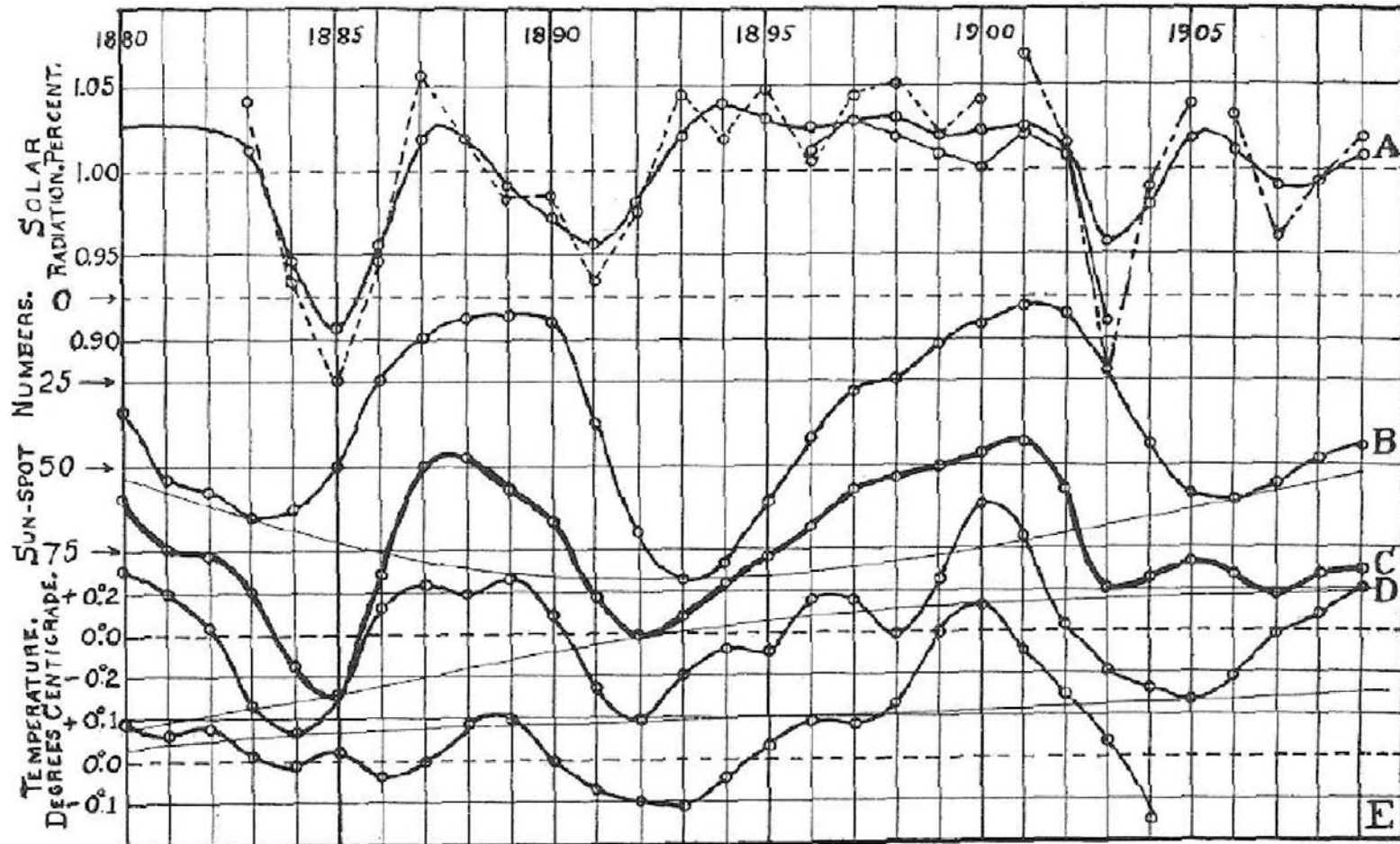
THE 1883 KRAKATAU ERUPTION CLIMATE EFFECTS



Observed extent from east to west of the ash cloud after the Krakatoa eruption. Numbers give the dates of observations (26 August to 9 September 1883) (from Symmons, 1888). The eruption had a «peculiar» effect on atmospheric pressure, showing a shock wave travelling around the globe. From [Schaller et al. \(2009\)](#), Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich (2009)



THE 1883 KRAKATAU ERUPTION CLIMATE EFFECTS

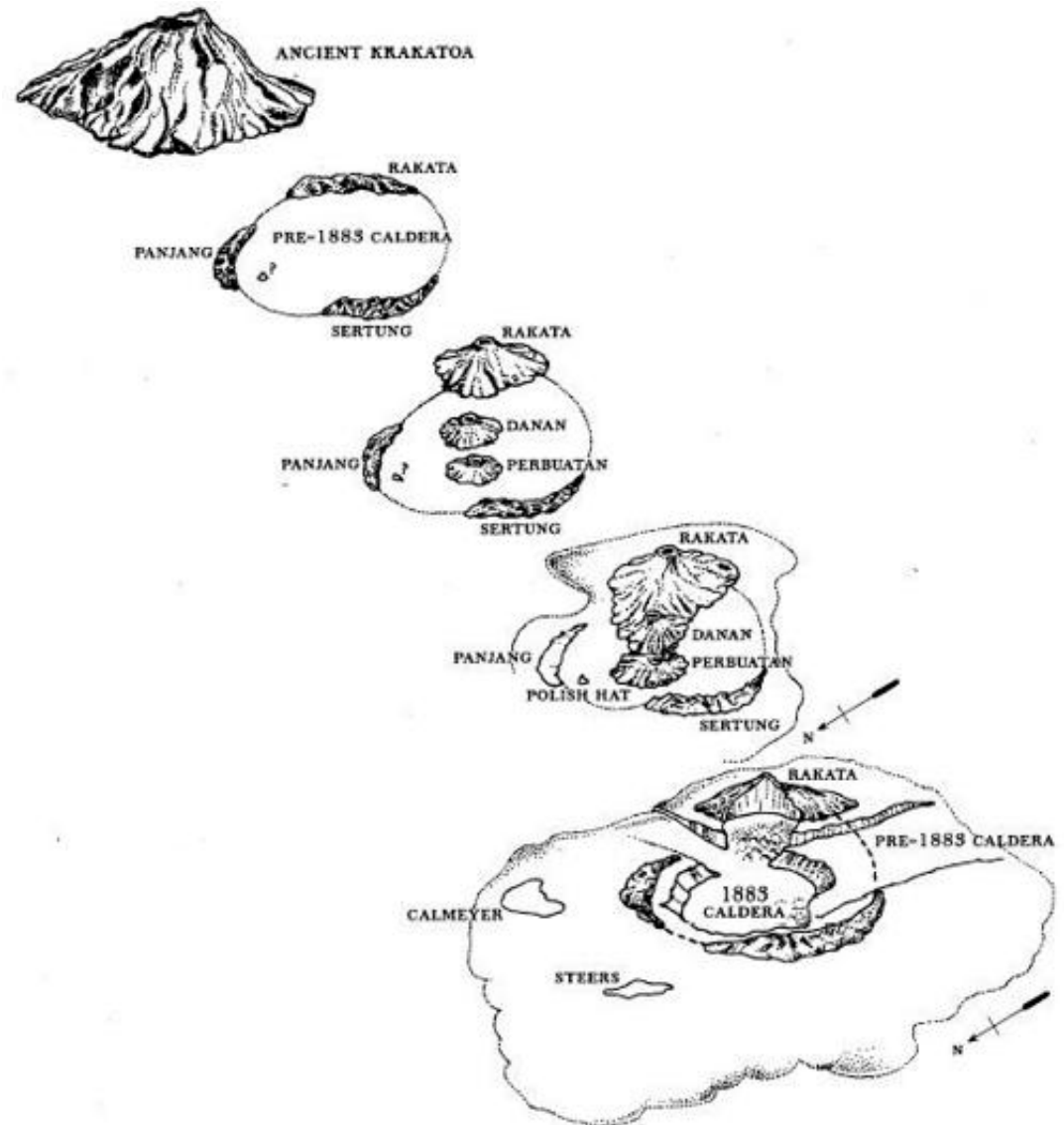
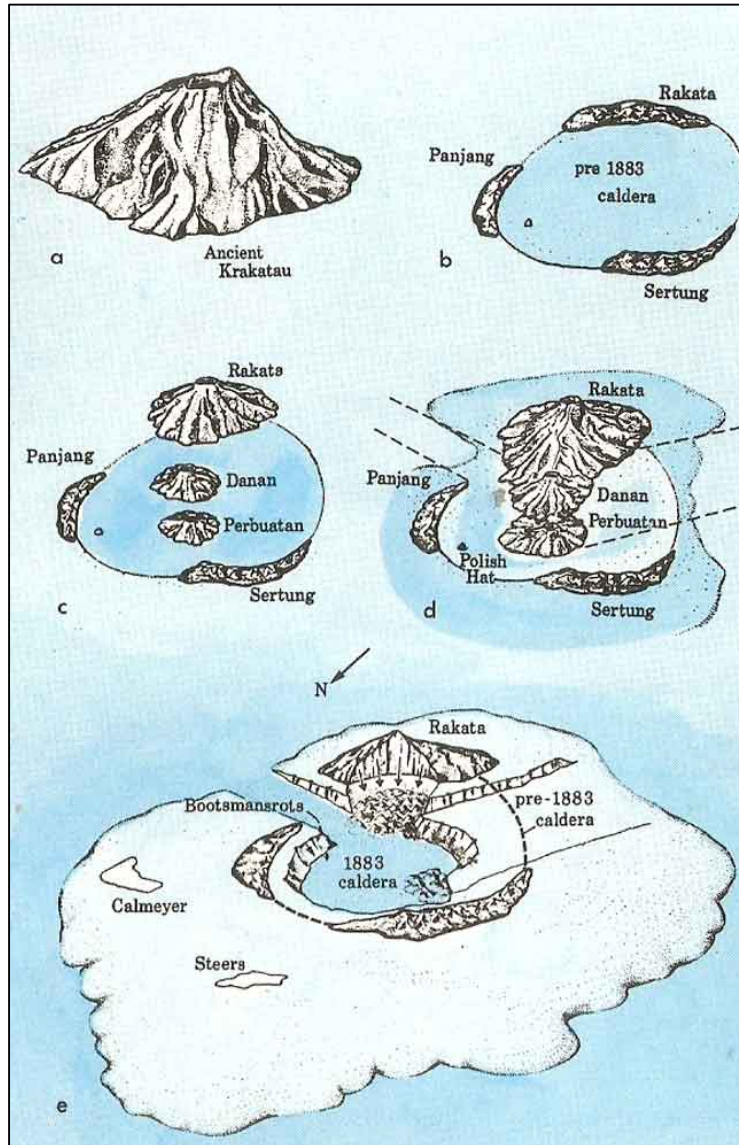


Solar radiation, sunspot number, and temperature from 1880 to 1910. A. Observed and smoothed annual mean noon solar radiation. B. Wolf's smoothed sun-spots numbers. C. Combined solar radiation and sun-spot numbers. D. Smoothed annual mean departures, United States maximum temperatures (15 stations). E. Smoothed annual mean departures, world temperature (47 stations) (from Abbot and Fowle, 1913).

From *Schaller et al. (2009)*, Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich (2009)

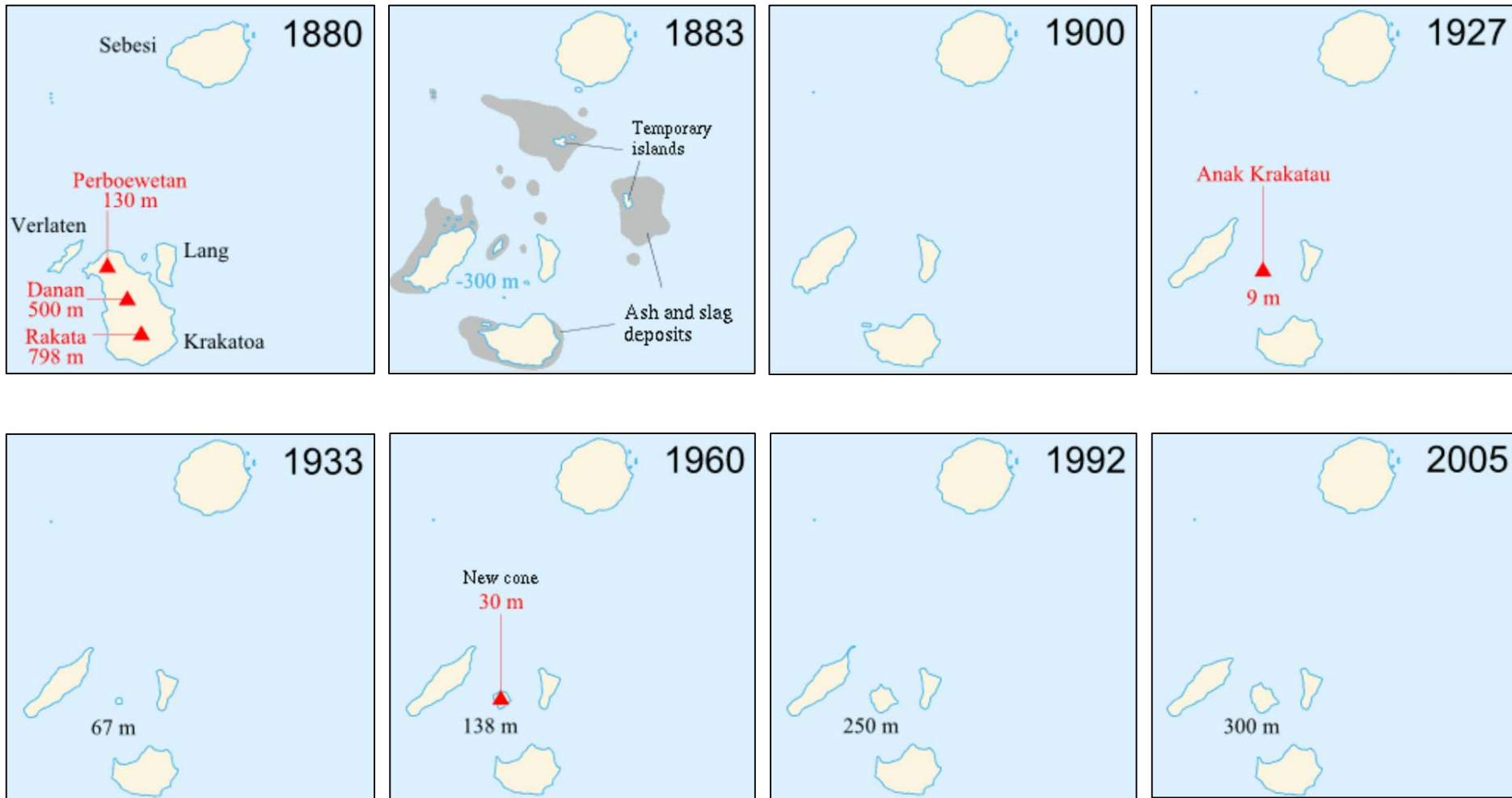


THE EVOLUTION OF KRAKATAU VOLCANIC COMPLEX FROM ANCIENT TIMES TO 1883 ERUPTION





THE EVOLUTION OF KRAKATAU VOLCANIC COMPLEX FROM 1880 TO 2005

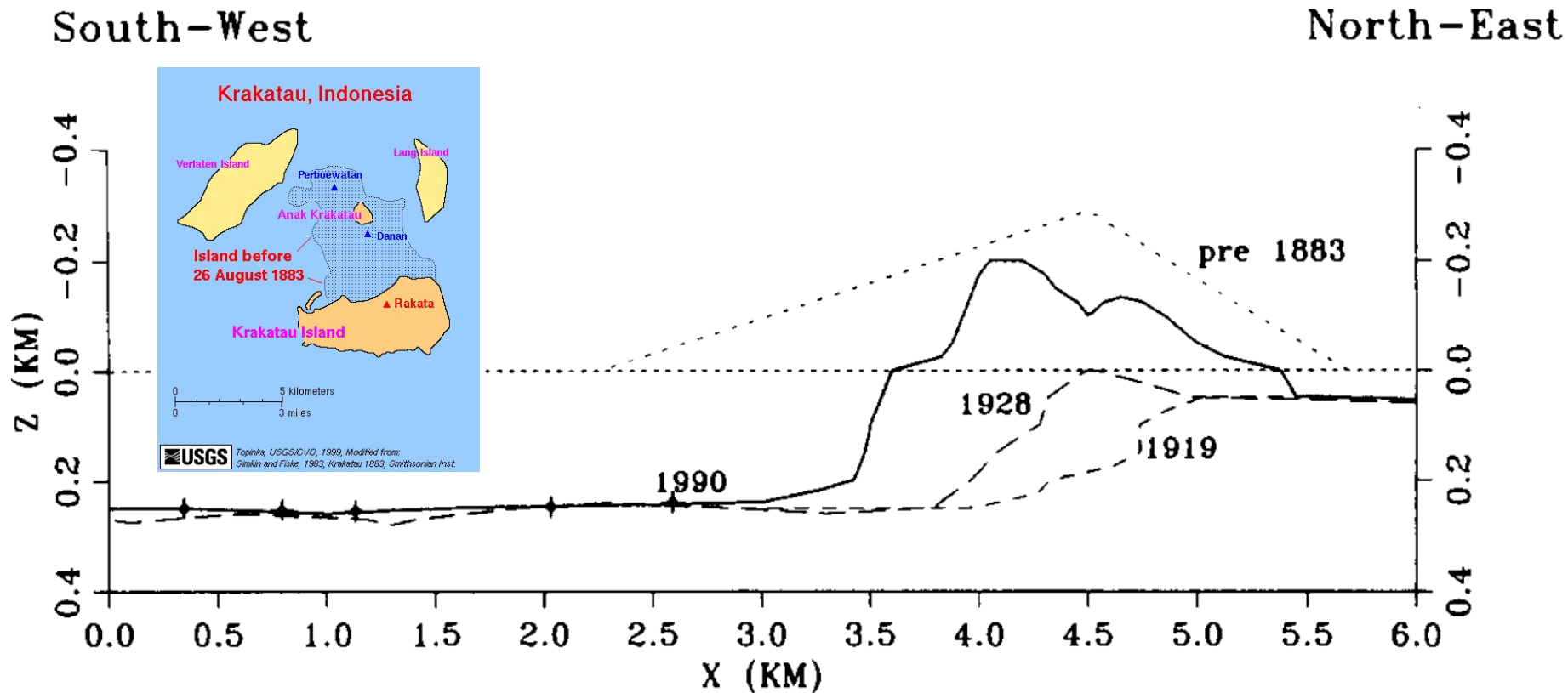


In **2017** the elevation of Anak Krakatau was reported as over 400 meters above sea level

https://en.wikipedia.org/wiki/File:Krakatoa_evolution_map-en.gif



THE MORPHOLOGICAL EVOLUTION OF ANAK KRAKATAU FROM 1883 TO 1990



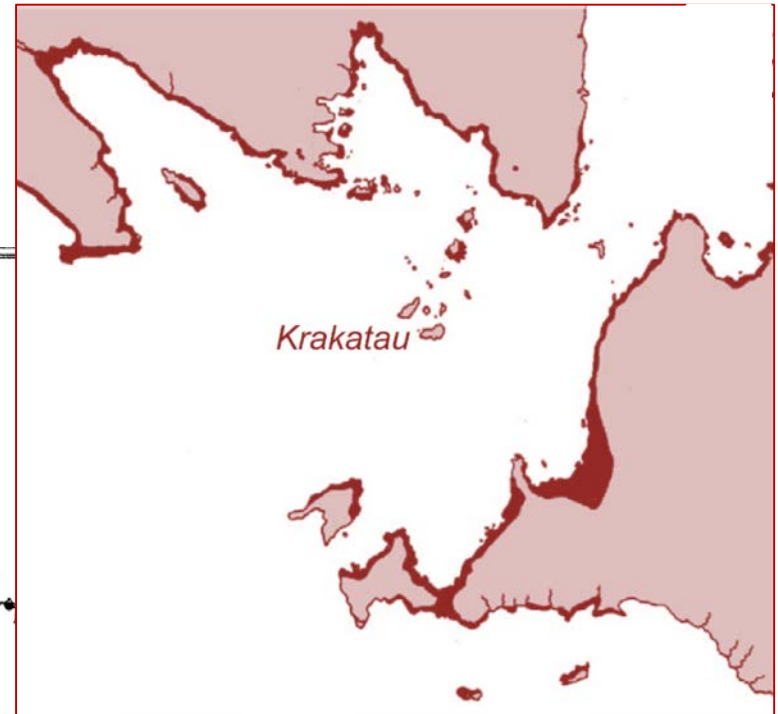
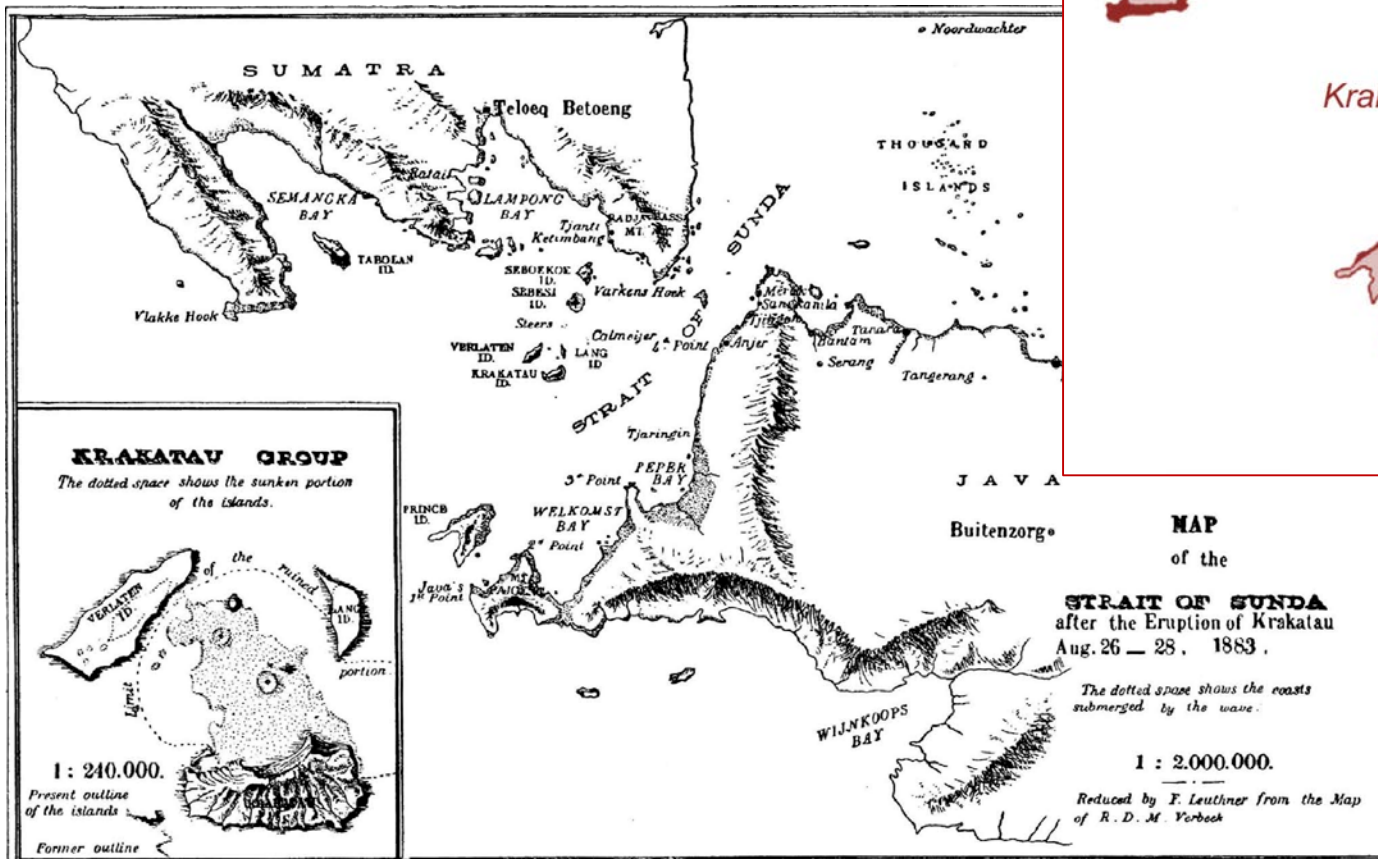
Morphological evolution with time of Anak Krakatau along a SW-NE line. Dashed lines below the sea level are the bathymetric profiles in 1919 and 1928. Solid line is the actual morphology of Anak Krakatau along which the nearest bathymetry data. Dashed line above the sea level shows the mean topography of the Krakatau island before the 1883 eruption.

From *Deplus et al. (1995)*, Journal of Volcanology and Geothermal Research



THE 1883 KRAKATAU ERUPTION SUBSEQUENT TSUNAMI AFFECTED THE COASTAL AREAS OF SUNDA STRAIT

- In red: coastal areas in the surroundings of Sunda Strait that were flooded by the 1883 Krakatau tsunami based on Simkin and Fiske (1983). From [van den Bergh et al. \(2003\)](#), *Marine Geology*

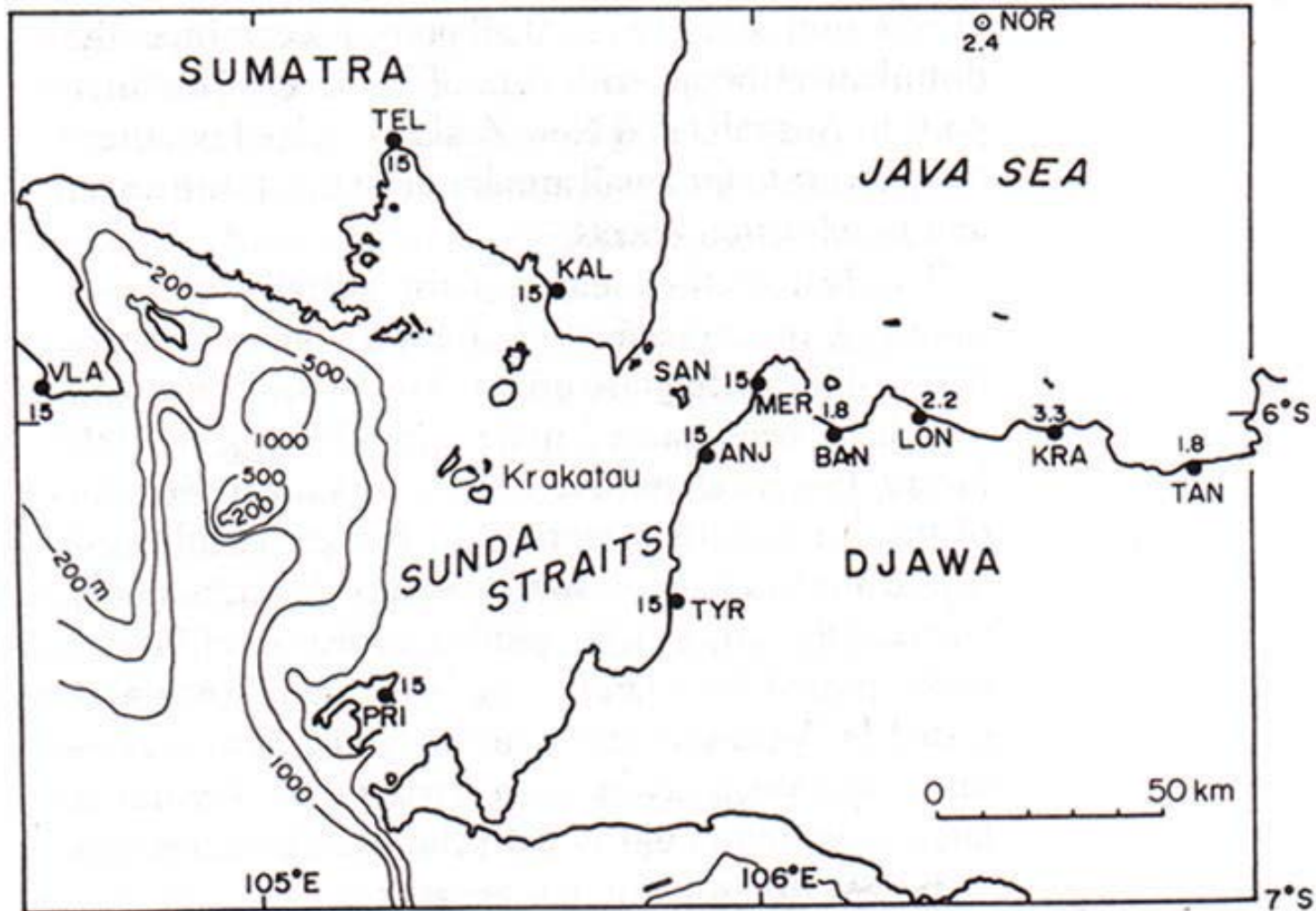


◀ Map of the Sunda Strait after the eruption of Krakatau (Hurlbut and Verbeek, 1887)

From [Schaller et al. \(2009\)](#), *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich* (2009)



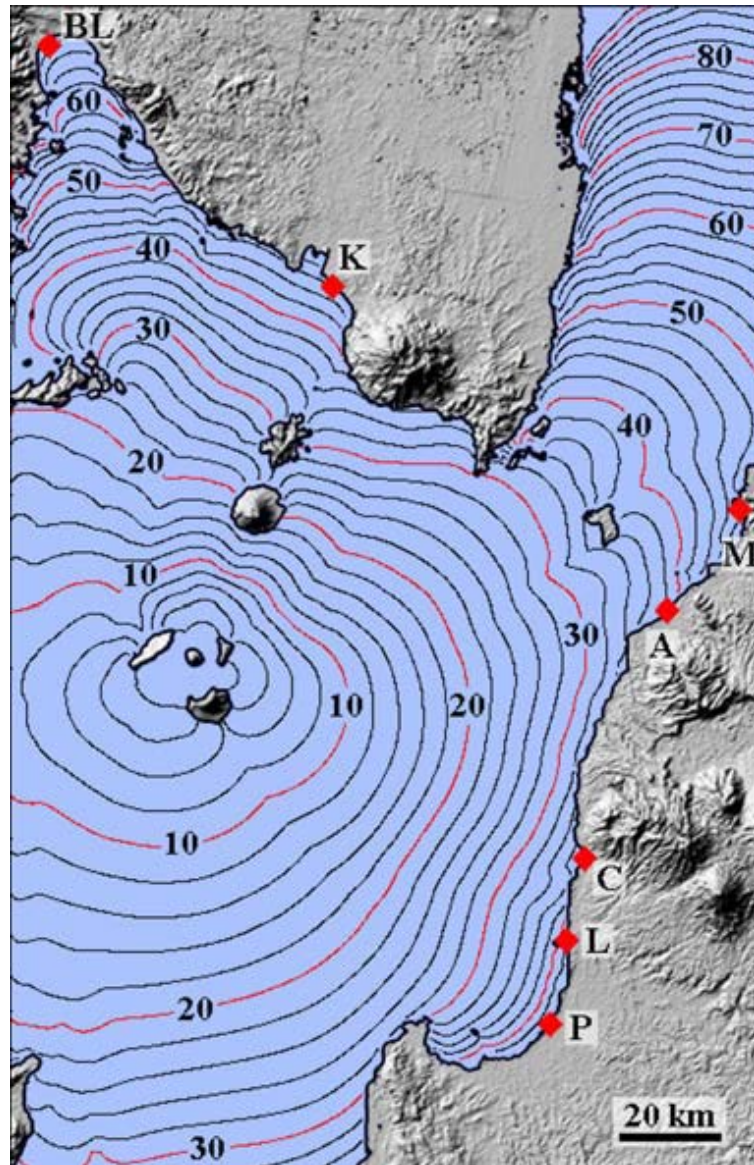
THE 1883 KRAKATAU ERUPTION SUBSEQUENT TSUNAMI AFFECTED THE COASTAL AREAS OF SUNDA STRAIT



Maximum run-up heights (in meters) of the tsunami of August 27, 1883 at coastal towns of Southern Sumatra and Western Java (Modified after Symons, 1888)



SIMULATION OF THE SUDDEN COLLAPSE OF ANAK KRAKATAU INTO THE 1883 CALDERA



Numerical simulation of the sudden collapse of Anak Krakatau Volcano into the 1883 caldera showed that all the coasts around the Sunda Strait could potentially be affected by waves of more than 1.0 m in less than 1 h after the event.

First wave travel time (expressed in min) for the first 90 min of simulation. Black lines are at 2 min intervals. Main coastal cities are shown by red diamonds. The impact of the sudden increase in water depth westwards from the Krakatau Archipelago is clearly seen, the waves being more rapid than those crossing the shallow strait. BL: Bandar Lampung; K: Kalianda; M: Merak; A: Anyer; C: Carita; L: Labuhan; P: Panimbang.

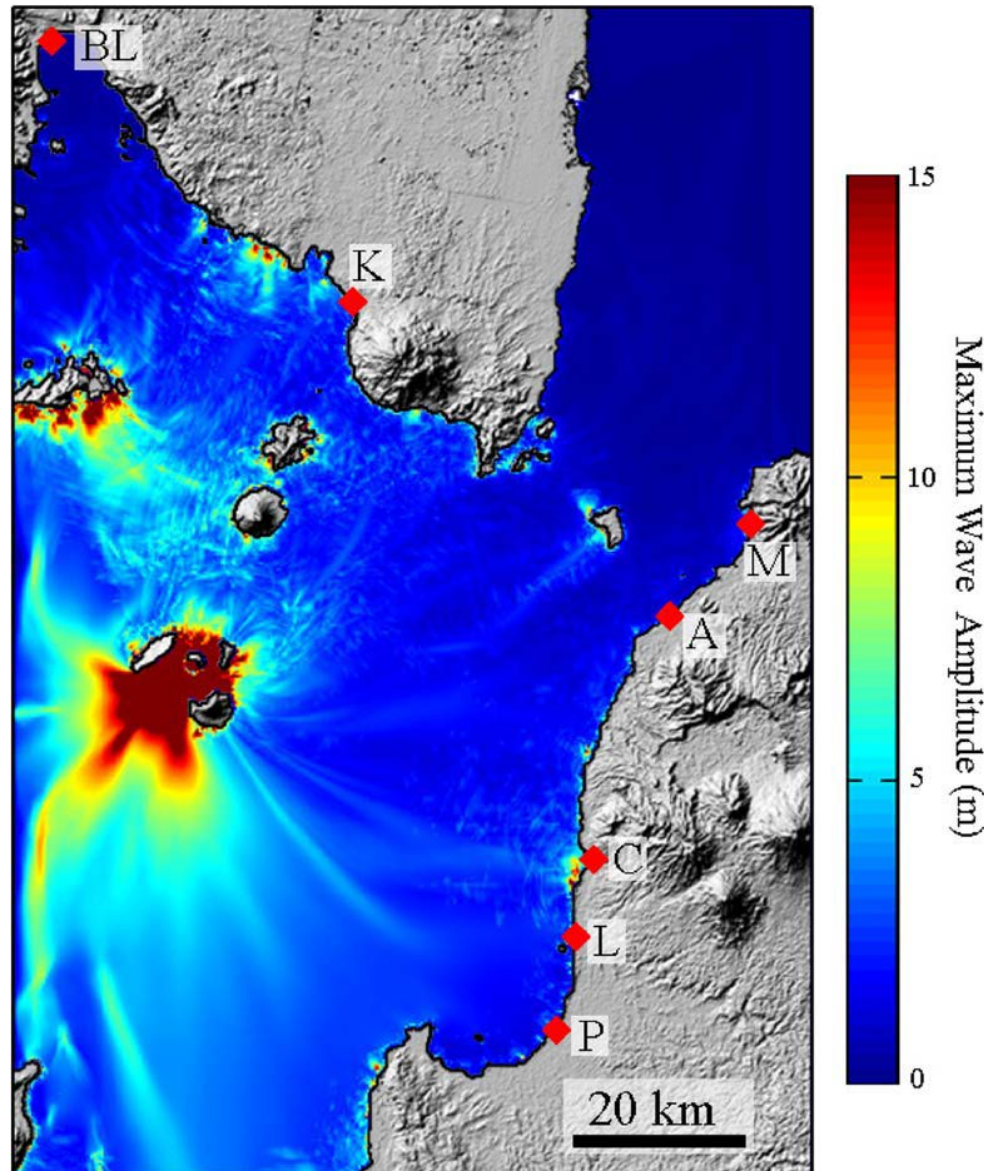
Based on eyewitnesses, the December 2018 tsunami arrived at the coast of western Java 24 minutes after an eruption of Anak Krakatau volcano.

From *Giachetti et al (2012)*

Geological Society, London, Special Publications, 361



SIMULATION OF THE SUDDEN COLLAPSE OF ANAK KRAKATAU INTO THE 1883 CALDERA



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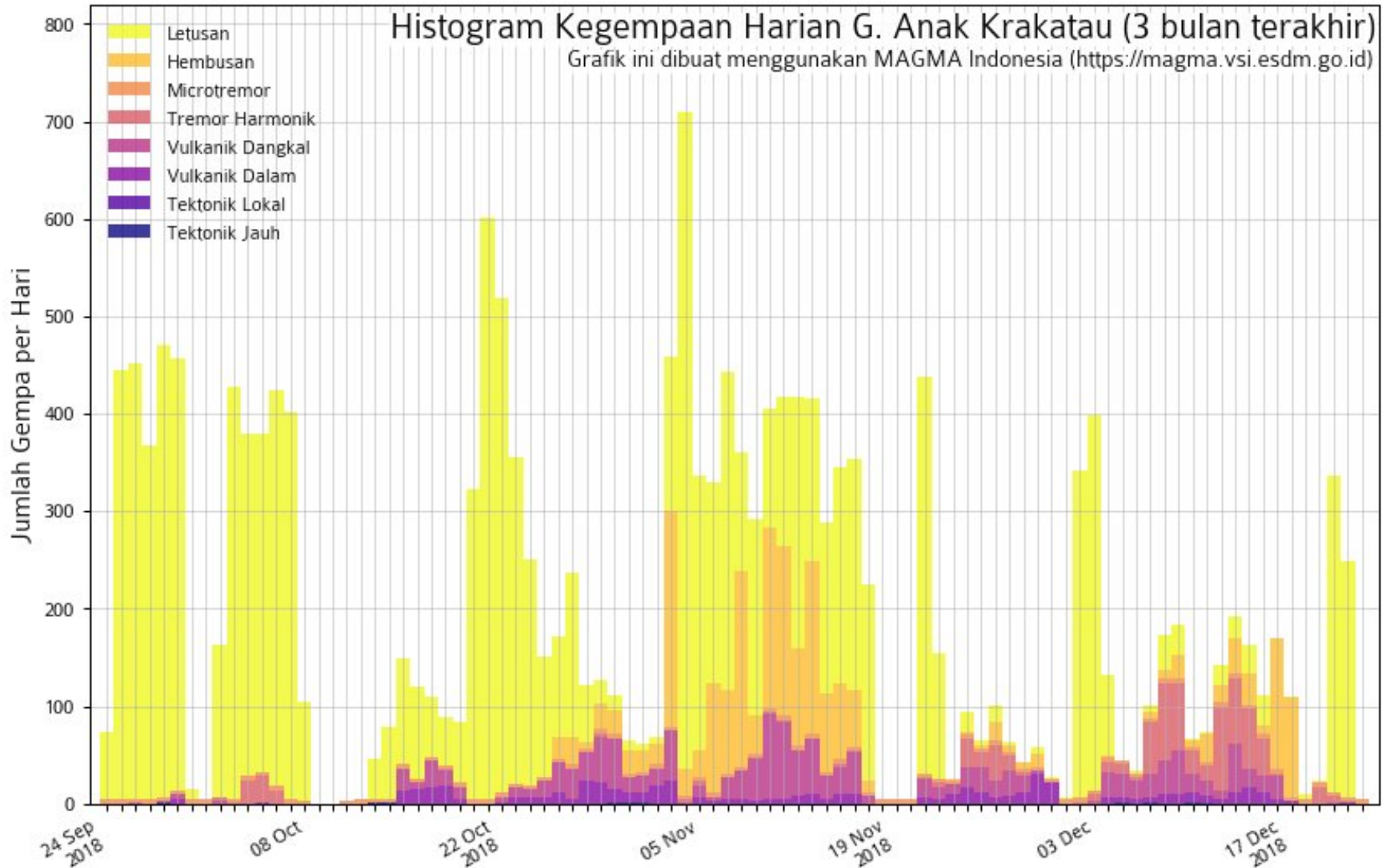
Maximum wave amplitude (m) recorded over 6000s of simulation, using a constant retarding stress of 10kPa to simulate the landslide propagation are illustrated.

Based on eyewitnesses, the December 2018 tsunami arrived at the coast of western Java 24 minutes after an eruption of Anak Krakatau volcano.

From *Giachetti et al (2012)*
Geological Society, London, Special Publications, 361



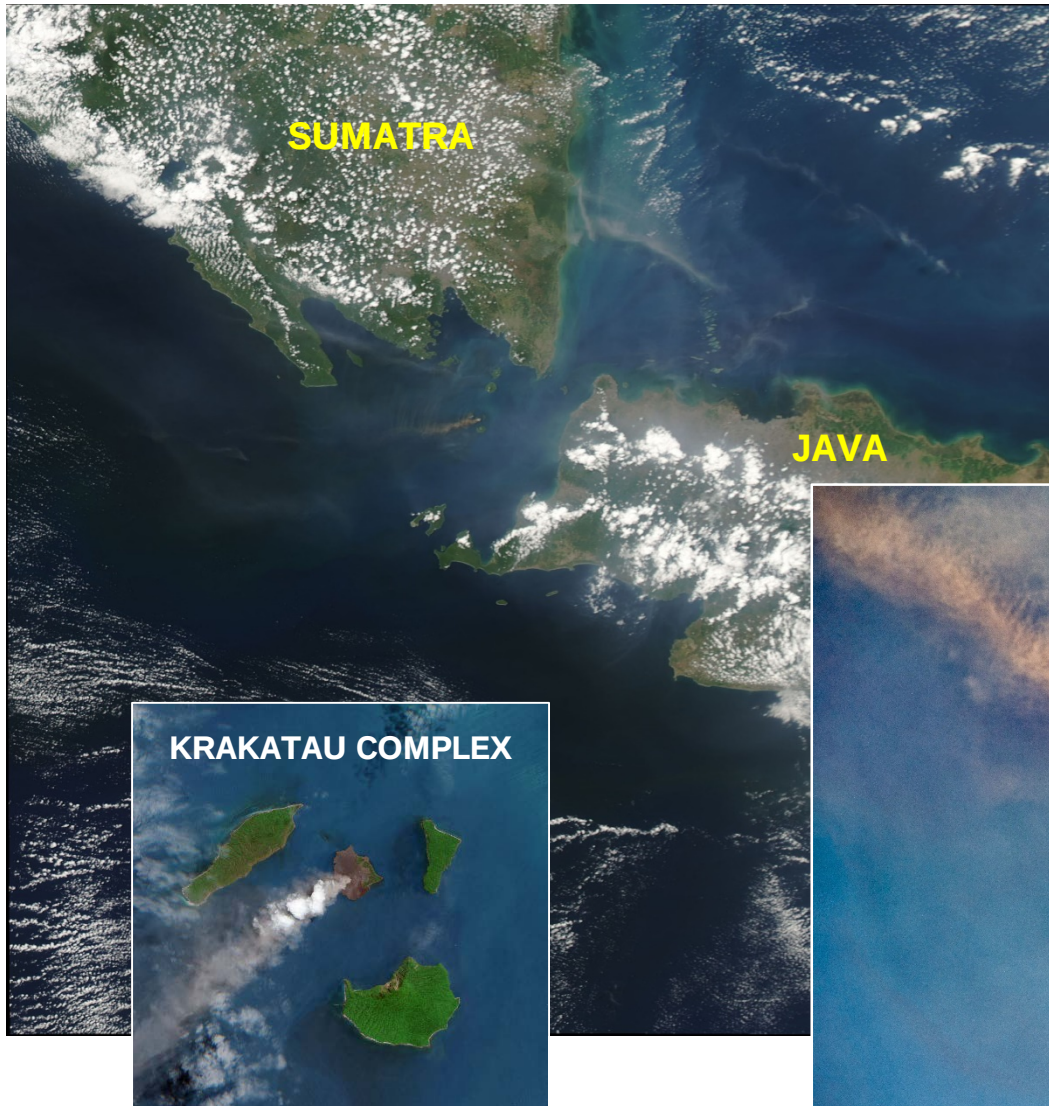
EVOLUTION OF THE ANAK KRAKATAU BEHAVIOR OVER THE PAST 3 MONTHS



The eruption and seismicity of Anak Krakatau over the past 3 months. Almost every day Mount Anak Krakatau erupts resulting in Alert Status. Anak Krakatau is still in the growth stage and his body is 4-6 meters higher per year.



EVOLUTION OF THE ANAK KRAKATAU BEHAVIOR OVER THE PAST 3 MONTHS



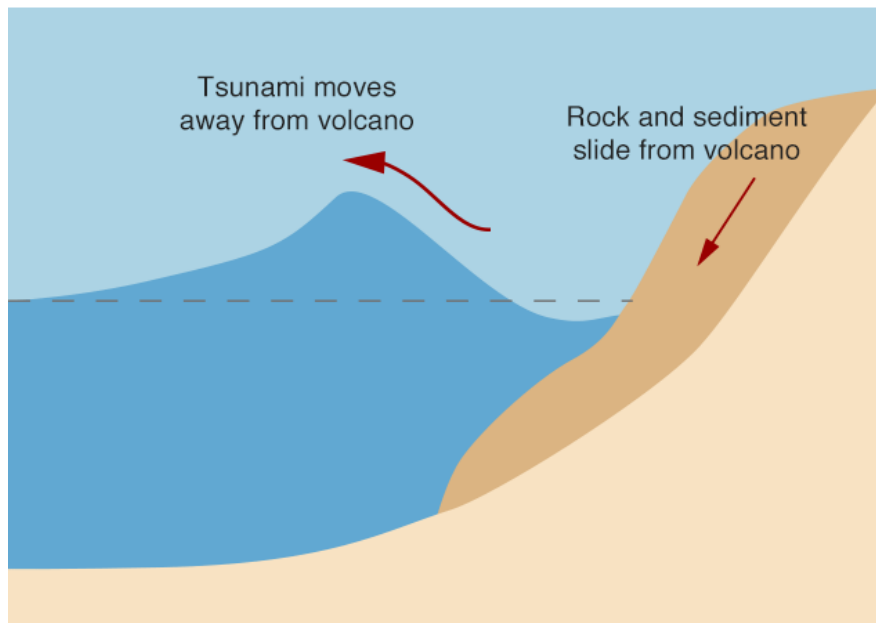
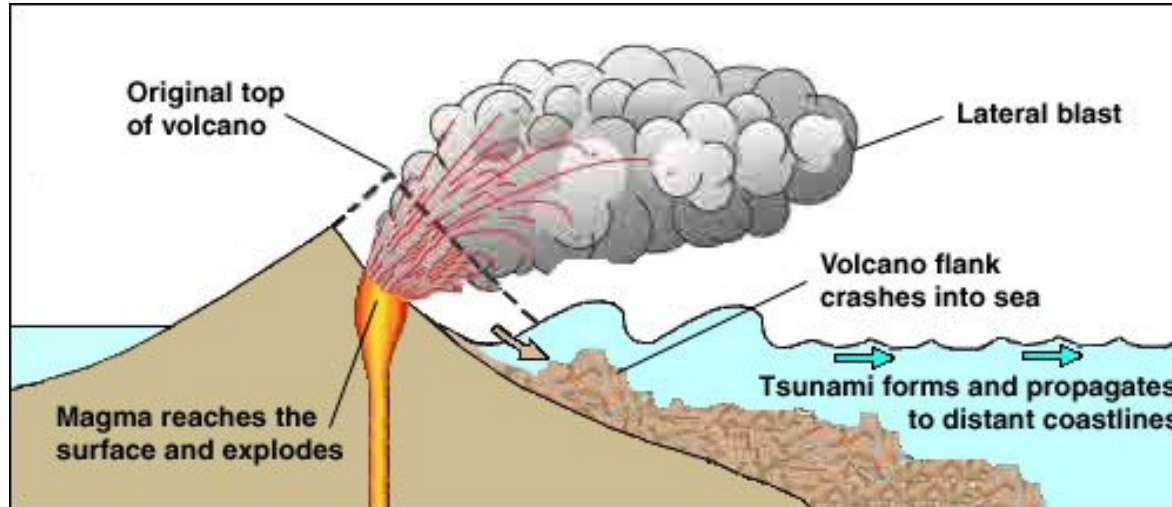
Activity at the Indonesian volcano Anak Krakatau is not unusual; eruptions have occurred sporadically over the past few decades. It is somewhat unusual, however, for satellites to get cloud-free views, as they did in September 2018.

Local sources reported that this eruption has been ongoing since June 19, 2018. Ash plumes have been observed rising to altitudes up to 1.8 km (6,000 ft). The plume was also visible from the International Space Station. European Space Agency astronaut Alexander Gerst snapped this photograph of the plume on September 24.





GENERATION OF THE DECEMBER 2018 INDONESIAN TSUNAMI

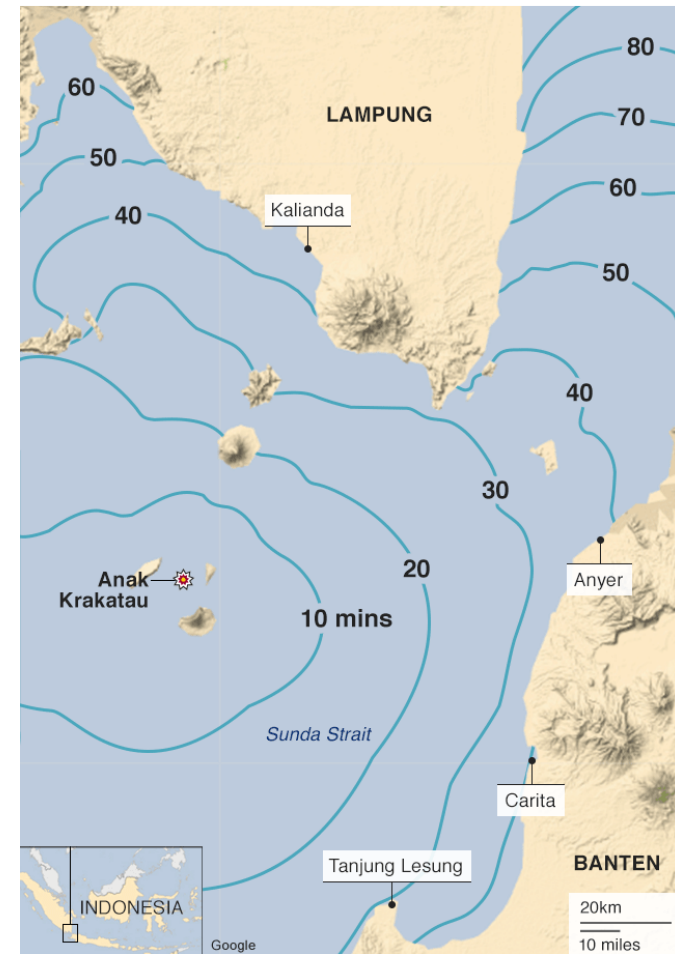


Source: BBC and University of California, Santa Cruz

BBC

Simulation of wave times based on collapse of SW flank of volcano

— Wave position (10 minute intervals)

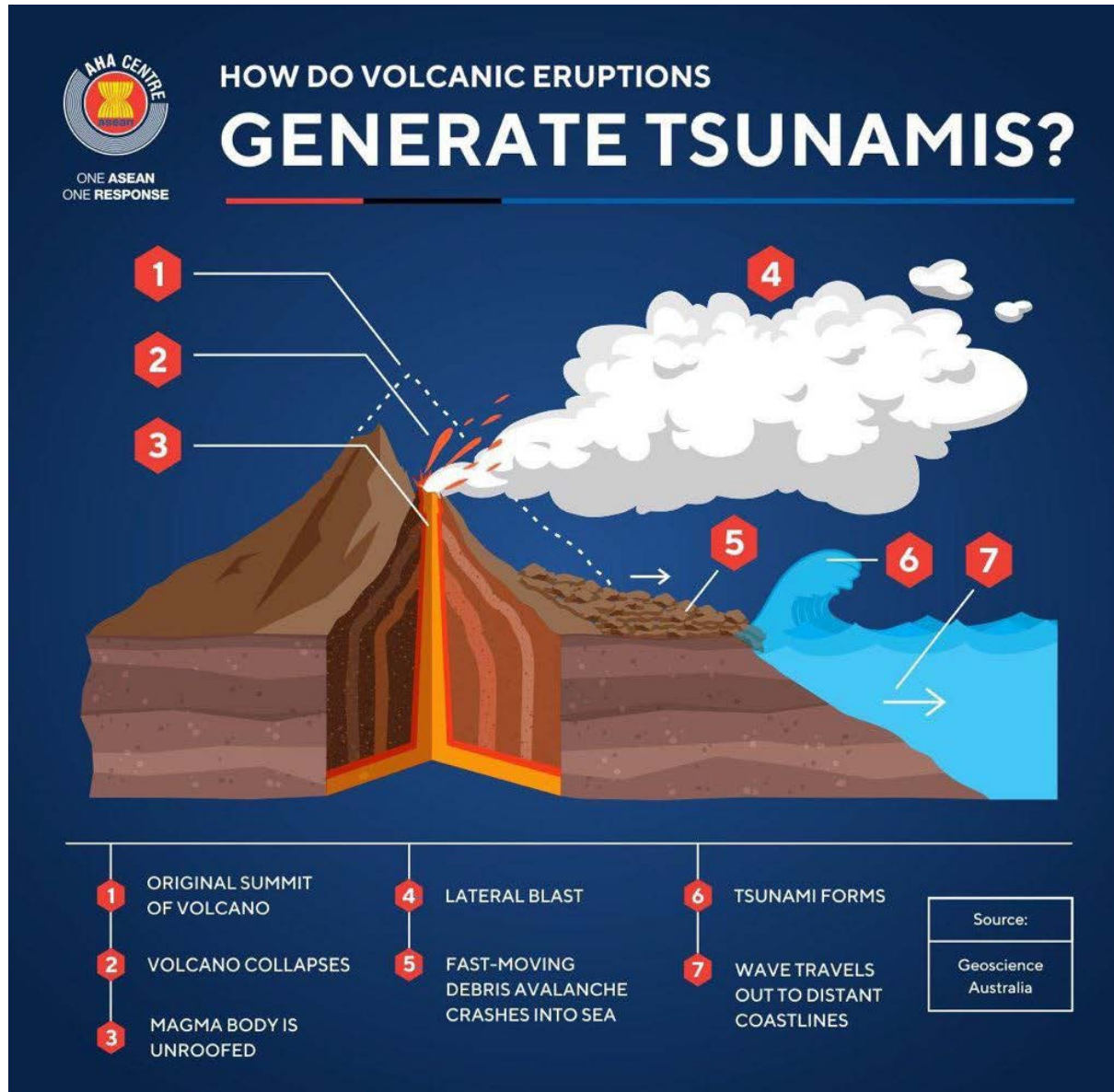


Source: Geological Society, London, Special Publications, 2012

BBC

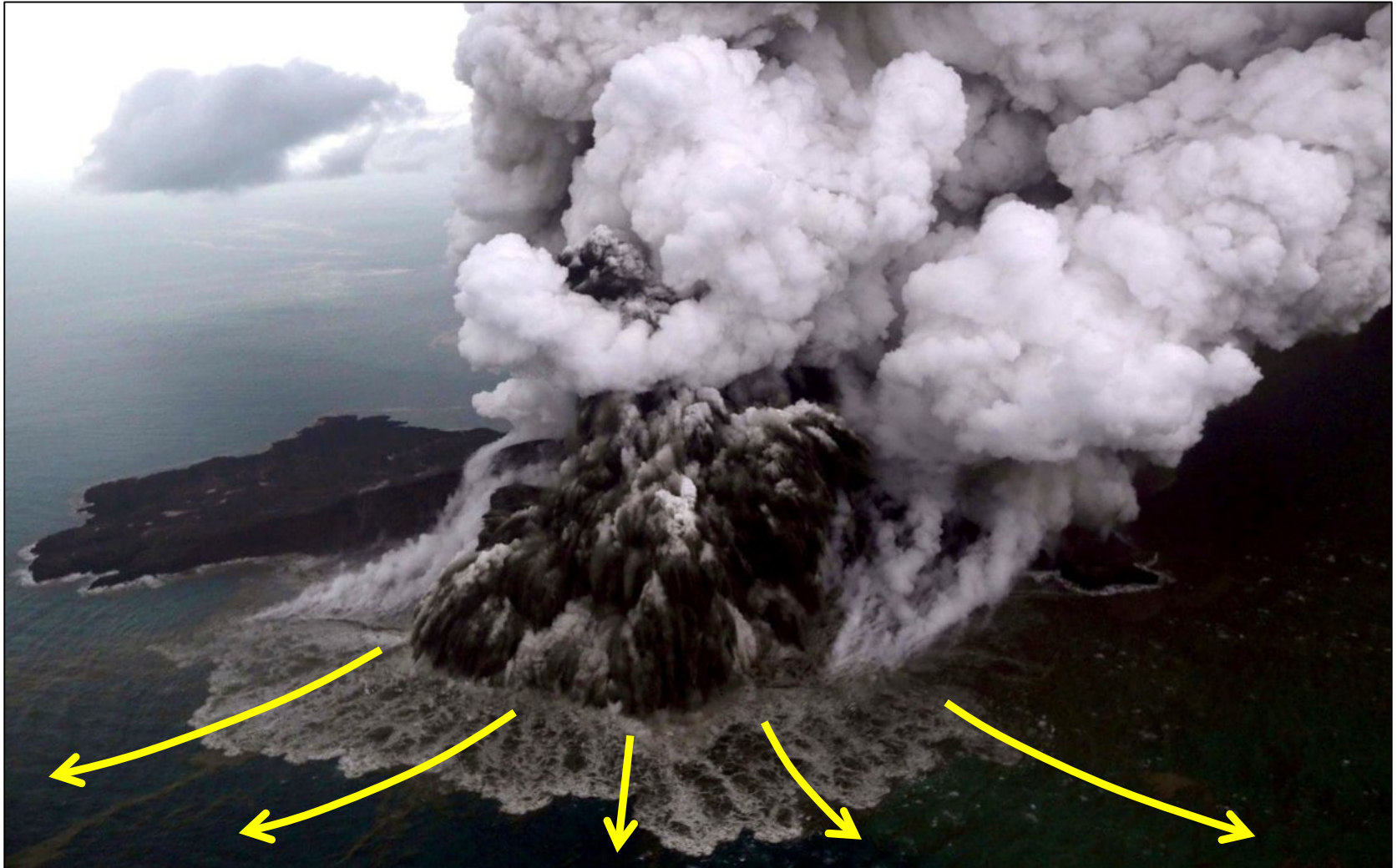


GENERATION OF THE DECEMBER 2018 INDONESIAN TSUNAMI





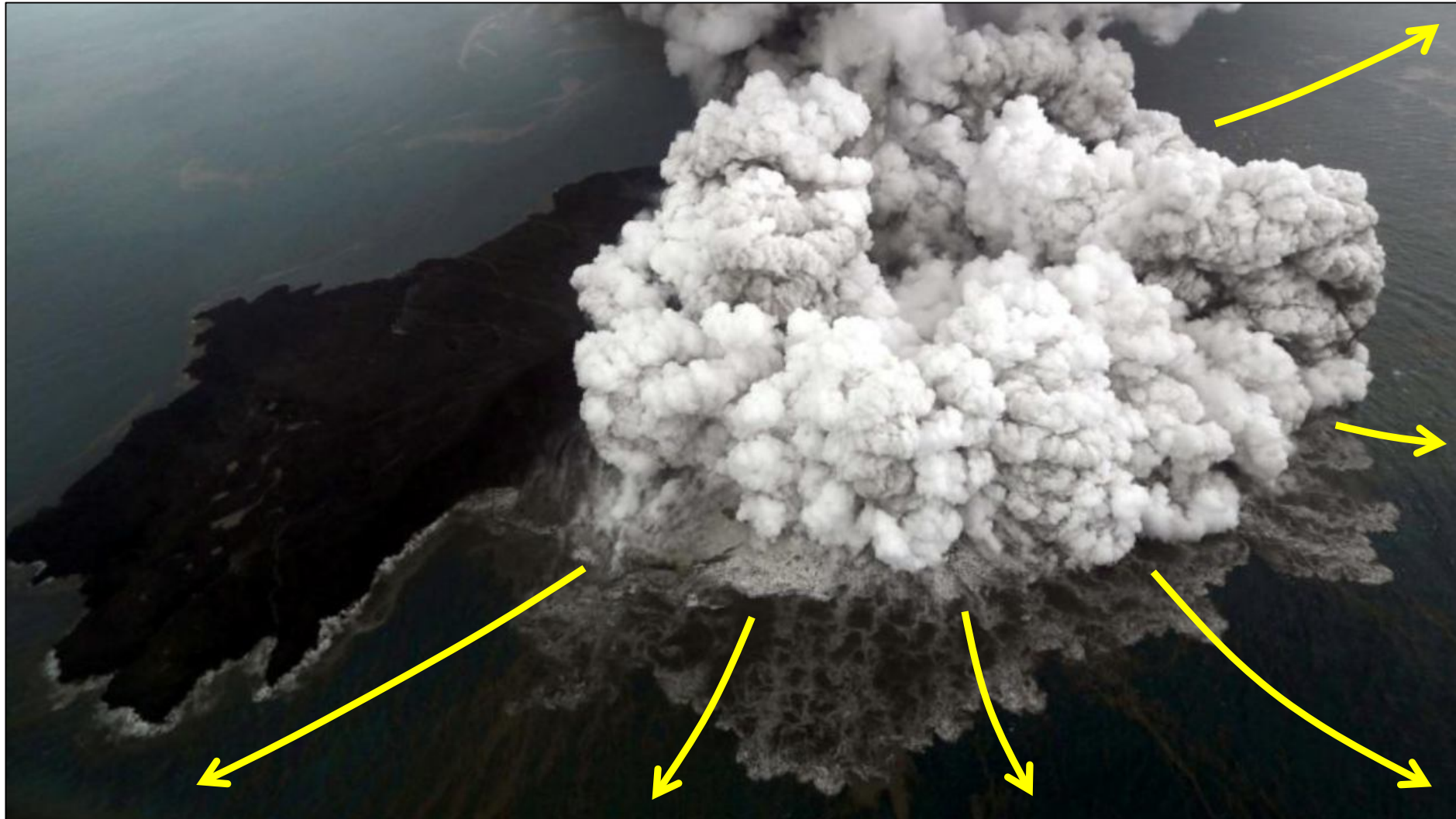
GENERATION OF THE DECEMBER 2018 INDONESIAN TSUNAMI



An aerial view of the Anak Krakatau volcano eruption during September 2018.
The volcano flank slides into the sea and a tsunami is generated.



GENERATION OF THE DECEMBER 2018 INDONESIA TSUNAMI

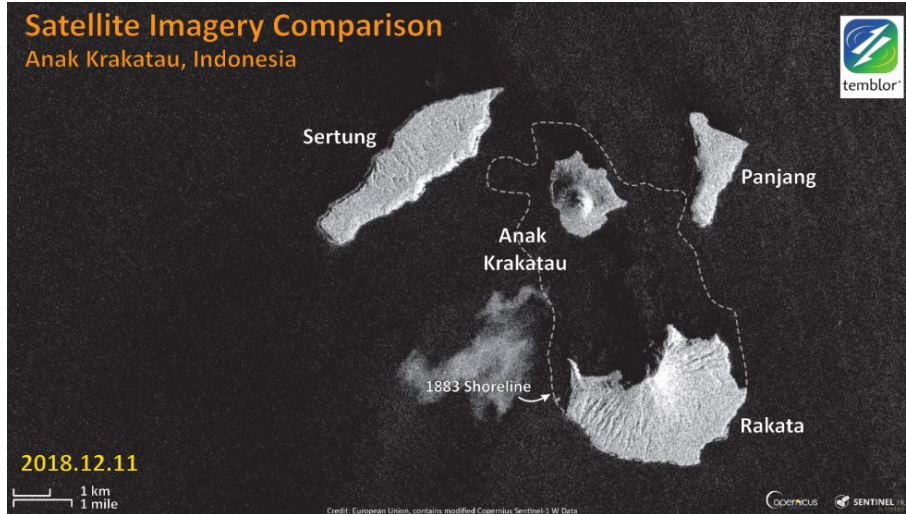


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The volcano flank slides into the sea and a tsunami is generated.

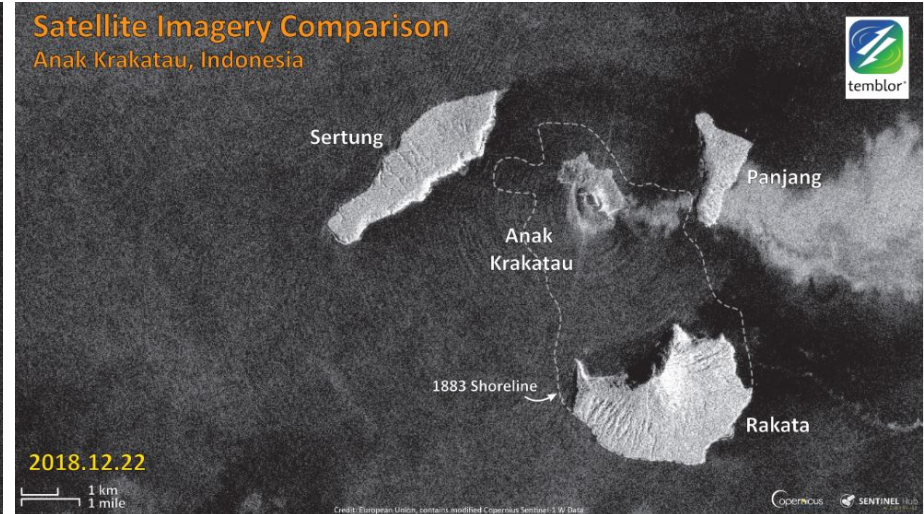


ORIGIN OF THE DECEMBER 2018 INDONESIA TSUNAMI

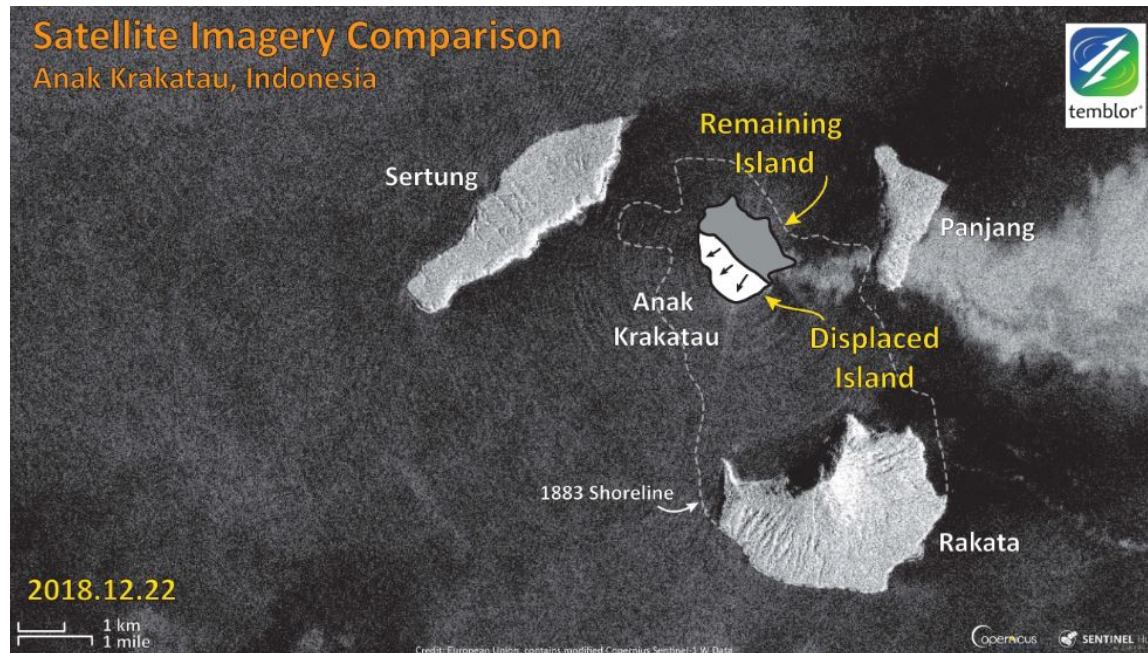
Satellite Imagery Comparison
Anak Krakatau, Indonesia



Satellite Imagery Comparison
Anak Krakatau, Indonesia

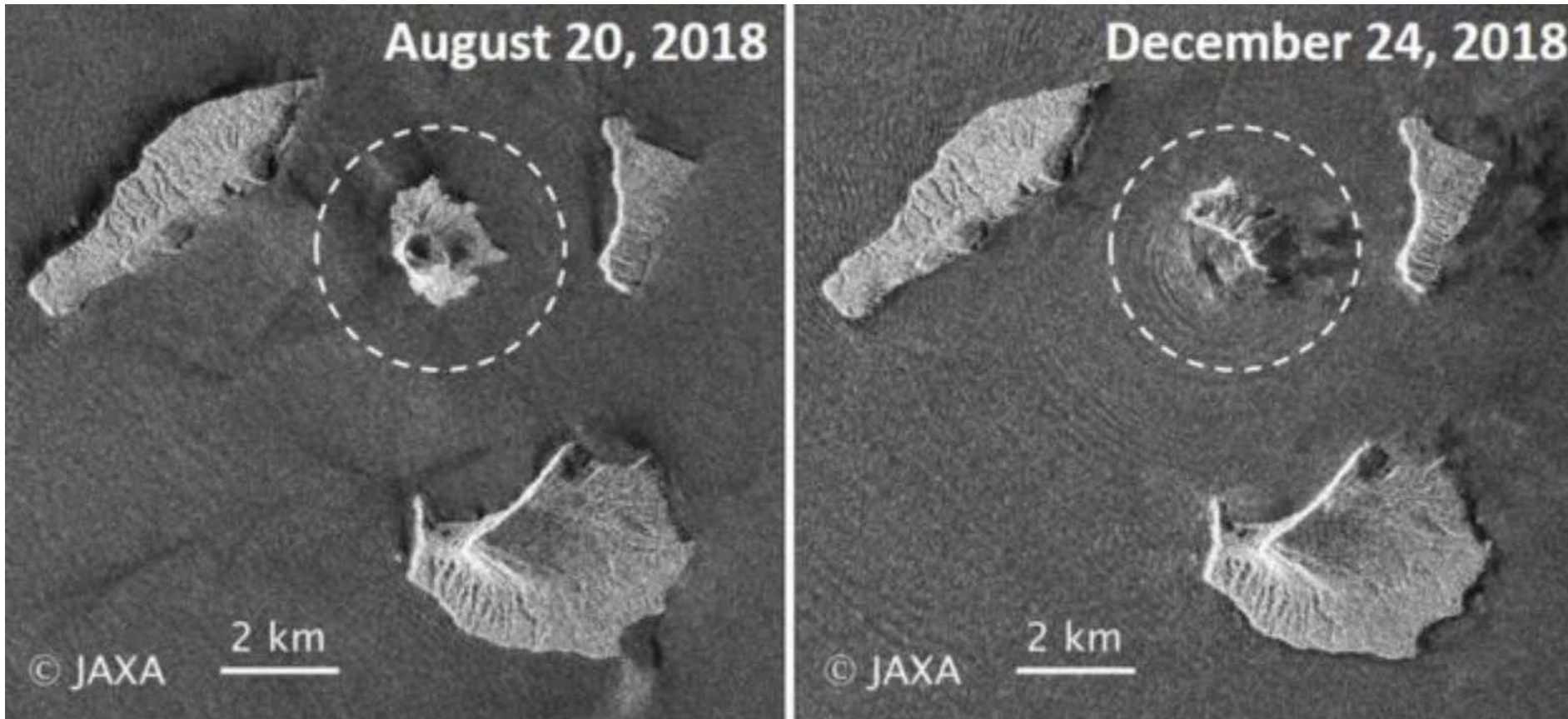


Satellite Imagery Comparison
Anak Krakatau, Indonesia





ORIGIN OF THE DECEMBER 2018 INDONESIAN TSUNAMI



The Japanese Alos-2 radar satellite used to monitor Anak Krakatau before and after the December 2018 tsunami disaster in Sunda Strait between Southern Sumatra and Western Java As it is indicated by the analysis of SAR intensity images of ALOS-2/PALSAR-2 data and the detected geomorphic changes caused by the eruption, the tsunami was most likely triggered by a chunk of the Anak Krakatau volcano slipping into the ocean. Geomorphic change is clearly detected in the southwestern part of the Anak Krakatau volcano. It can be estimated that approximately 2 km squares of southwestern part of the island was collapsed by December 24th at 5 pm (UTC).

From <http://www.gsi.go.jp/cais/topic181225-index-e.html>



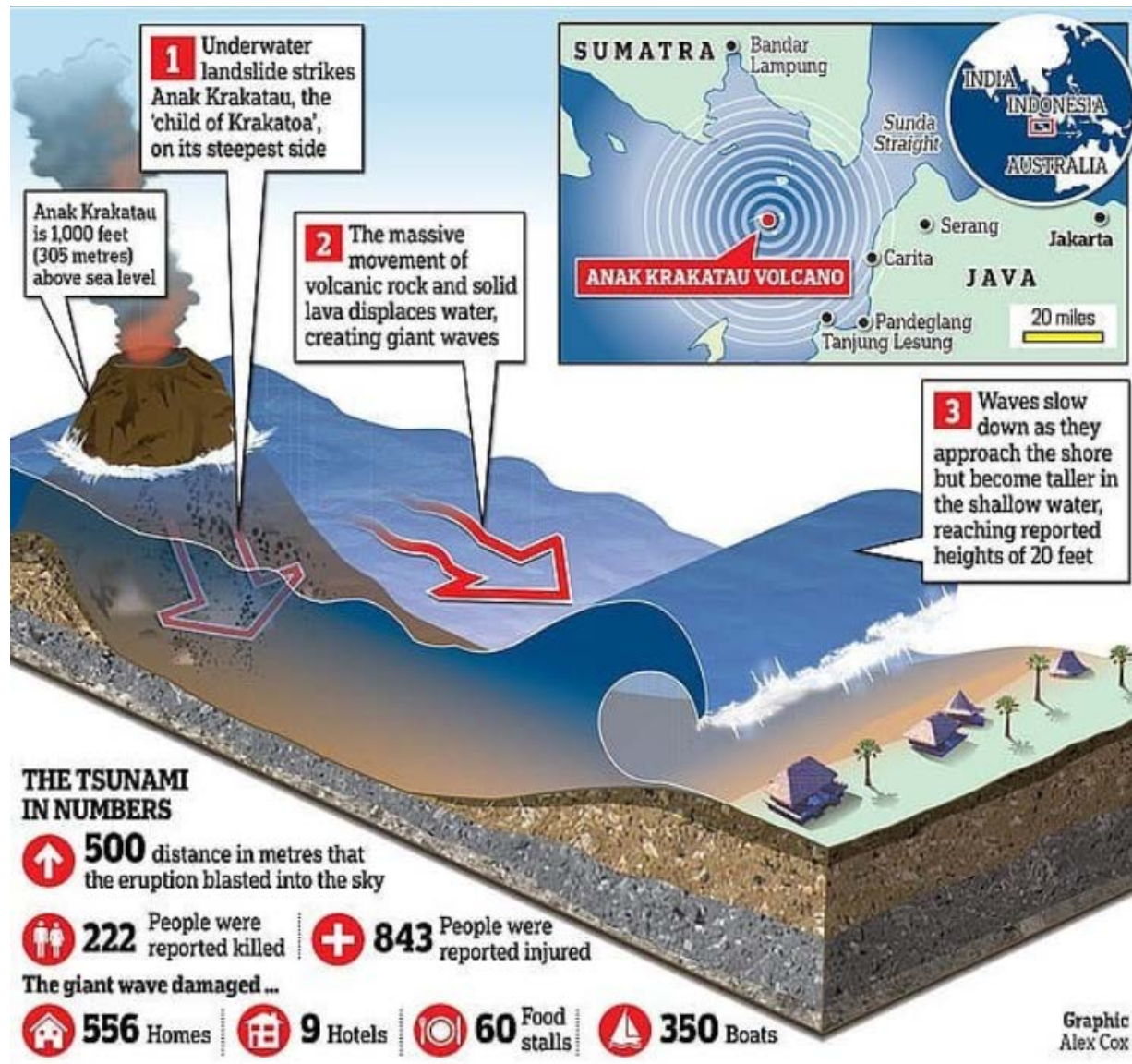
THE ERUPTION OF THE ANAK KRAKATAU A DAY AFTER THE TSUNAMI



A plume of ash rises as the Anak Krakatau volcano erupts in Sunda Strait, Indonesia on December 23, 2018



THE DEVASTATING POWER OF ANAK KRAKATAU

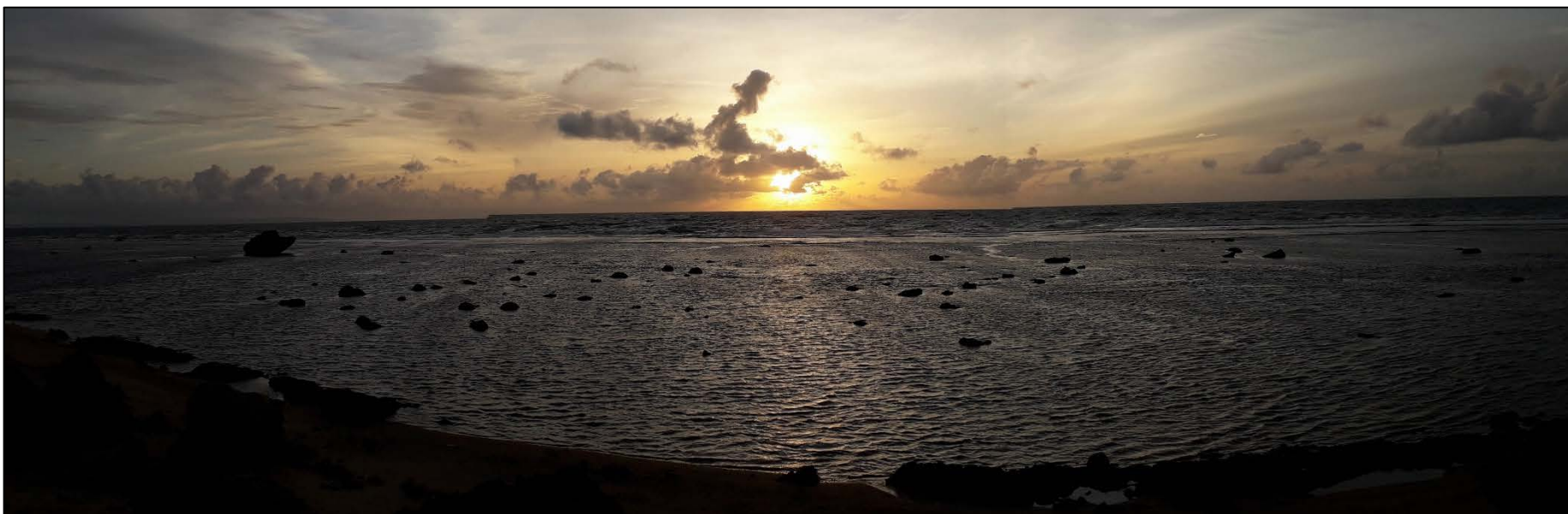




THE SHALLOW COASTAL AREA OF THE SEVERELY AFFECTED WESTERN JAVA



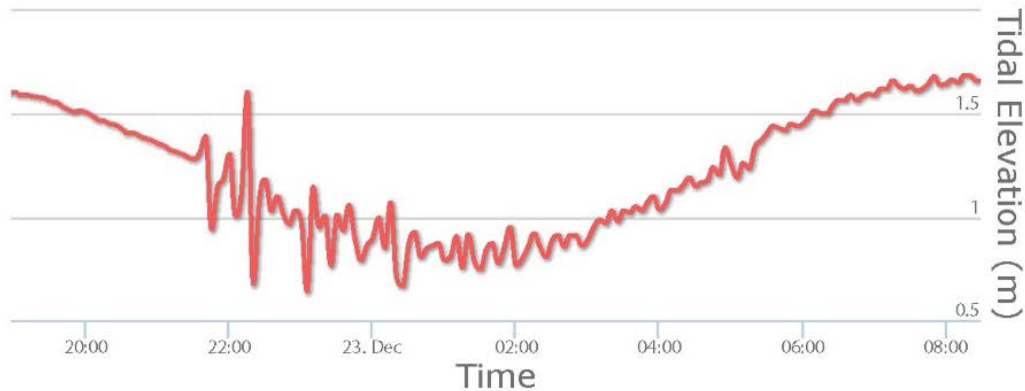
Panoramic view of the shallow coastal area of the western Java in Carita beach. The small depth increased the height of the waves and their devastating power along the coast resulting in severe structural damage in buildings and infrastructures and many fatalities.



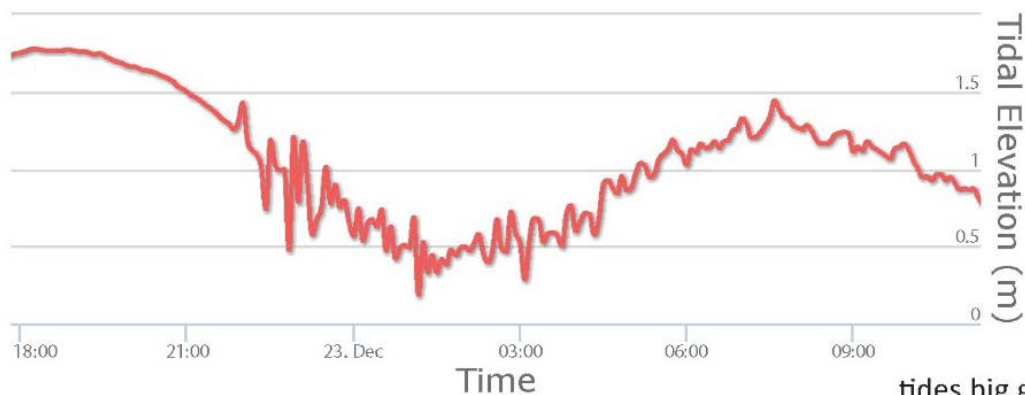


TIDE GAUGE RECORDS FROM THE SUNDA STRAIT

Station Banten, Java



Station Panjang, Sumatra

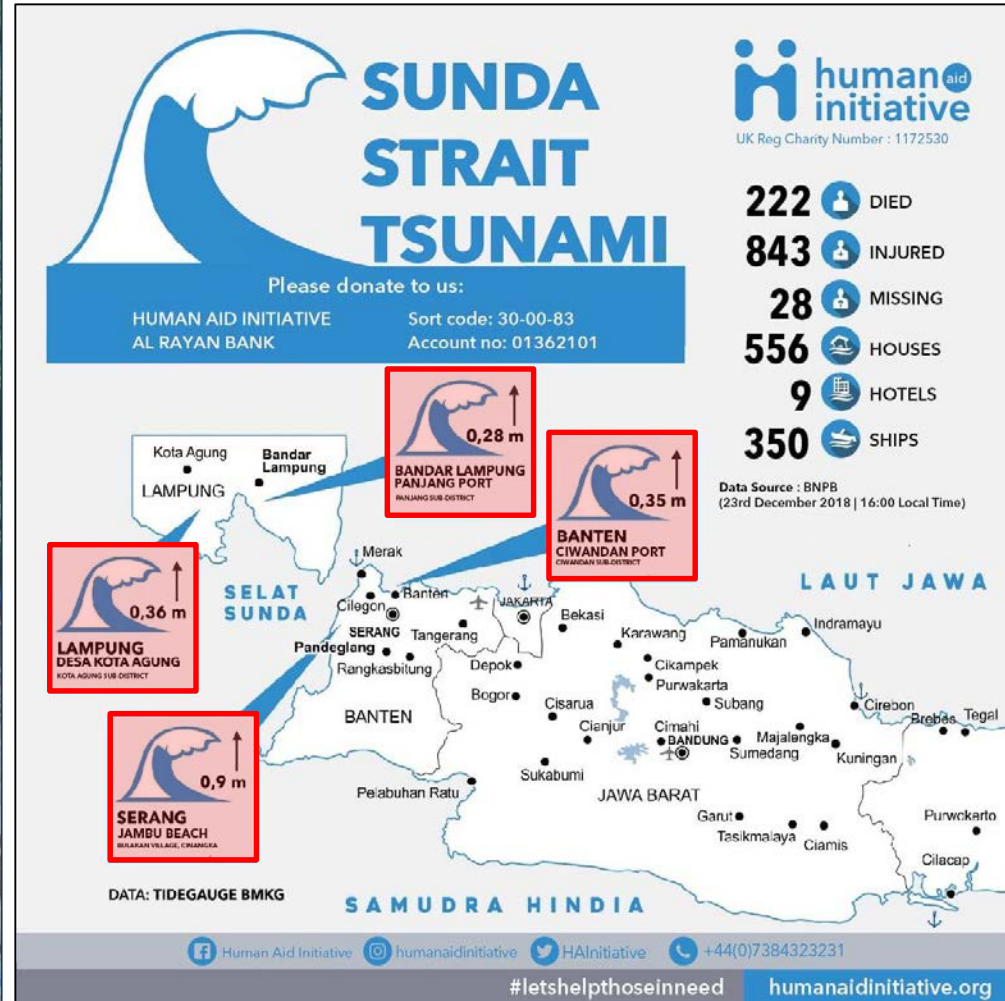


The tide gauge record reveals that there was about 40 minutes from the first wave arrival to the highest and most destructive inundation. So, even without an expensive tsunami warning system a warning was possible.

<http://temblor.net/earthquake-insights/sunda-strait-tsunami-launched-by-sudden-collapse-of-krakatau-volcano-into-the-sea-8081/>



WAVE HEIGHTS OF THE DECEMBER 2018 INDONESIAN TSUNAMI



Scars and marks on trees from tsunami in Carita beach (western Java)

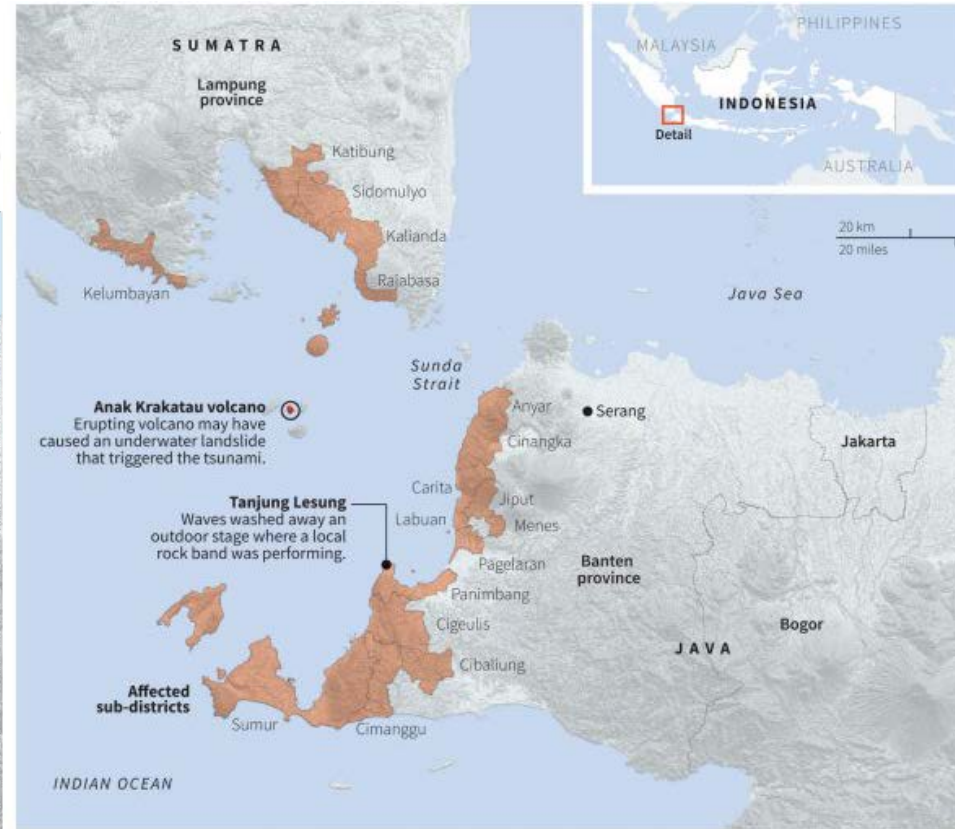


THE IMPACT OF THE DECEMBER 2018 INDONESIA TSUNAMI MOST AFFECTED COASTAL AREAS AND SUB-DISTRICTS



Sources: Reuters; Maps4news
W. Cai, 23/12/2018

REUTERS



Sources: Reuters; Maps4News; World Food Programme (Snapshot as of Dec. 23, 0900 GMT)
C. Inton, W. Cai, 24/12/2018

REUTERS



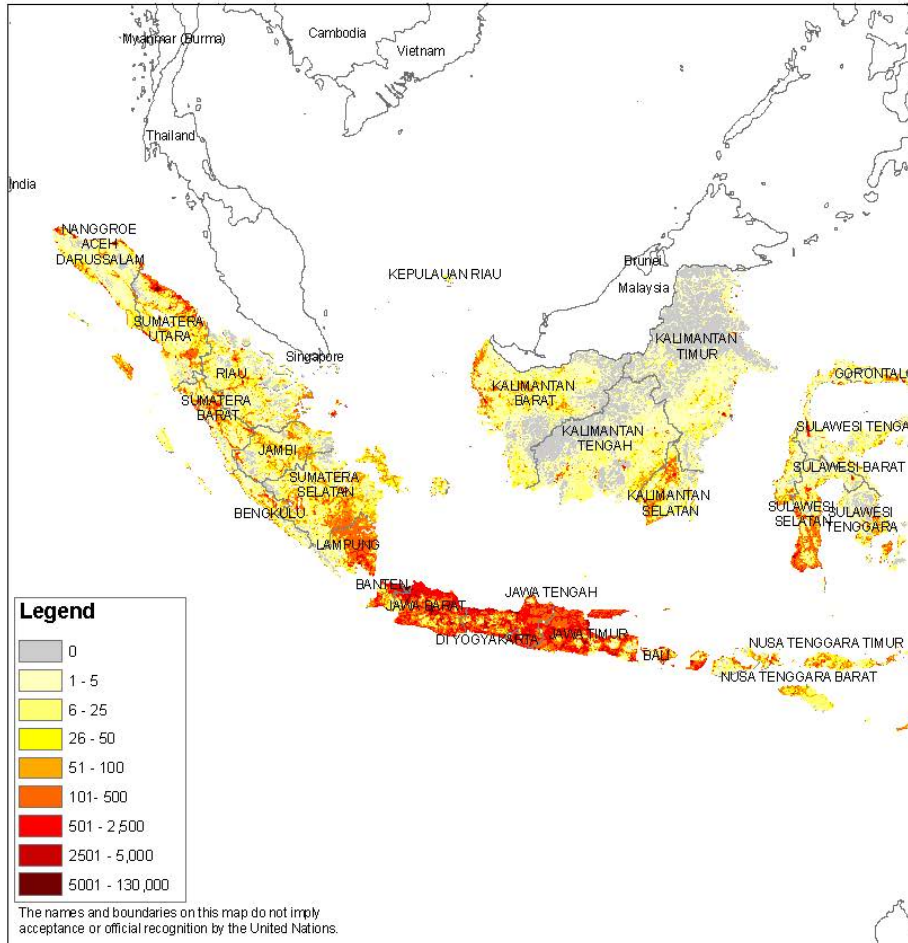
POPULATION DENSITY OF THE TSUNAMI AFFECTED AREA



UN Office for the Coordination of Humanitarian Affairs

INDONESIA - Population Density

05 March 2008

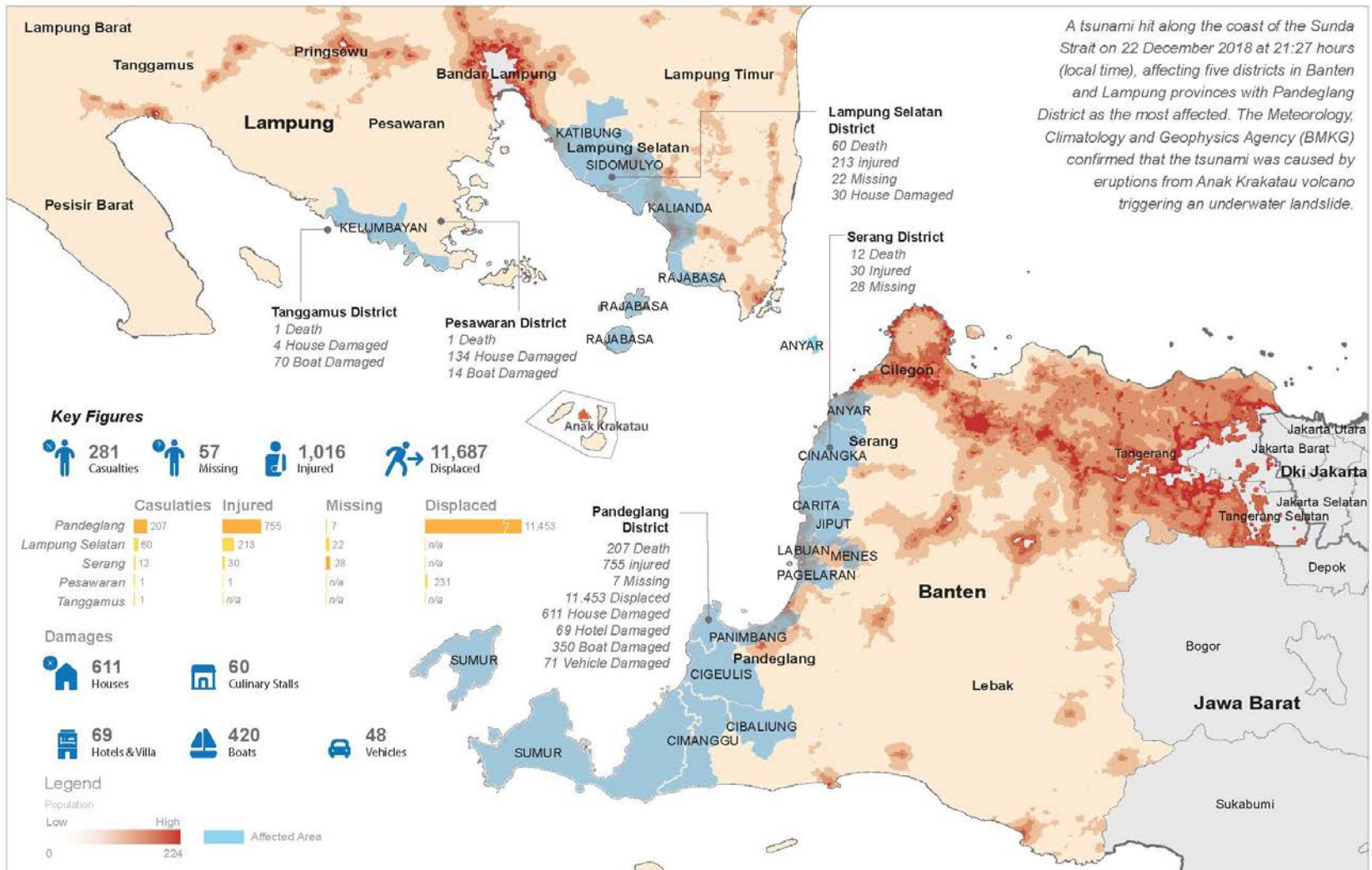


Source: NASA Socioeconomic Data and Application Center (SEDAC), data from 2015



IMPACT OF THE DECEMBER 2018 INDONESIA TSUNAMI

INDONESIA: Humanitarian Snapshot Sunda Strait Tsunami (as of 24 Dec 2018)

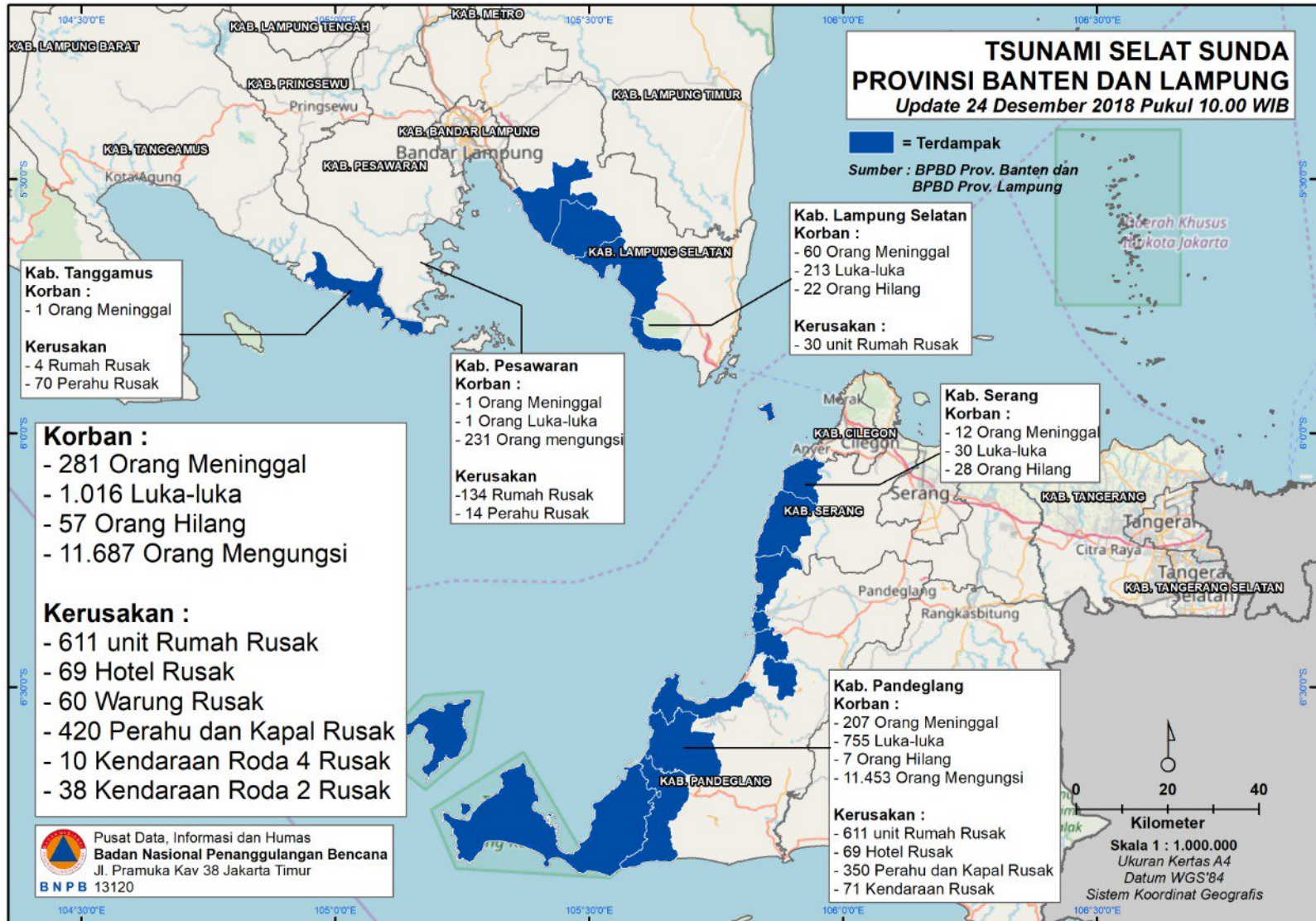


The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Creation date: 24 Dec 2018 Sources: OCHA, Indonesia Geospatial Agency (BIG), National Disaster Management Agency (BNPB), PVMBG, WorldPop Feedback: ocha-indonesia@un.org www.unocha.org <http://humanitarianresponse.info/operations/indonesia> www.reliefweb.int

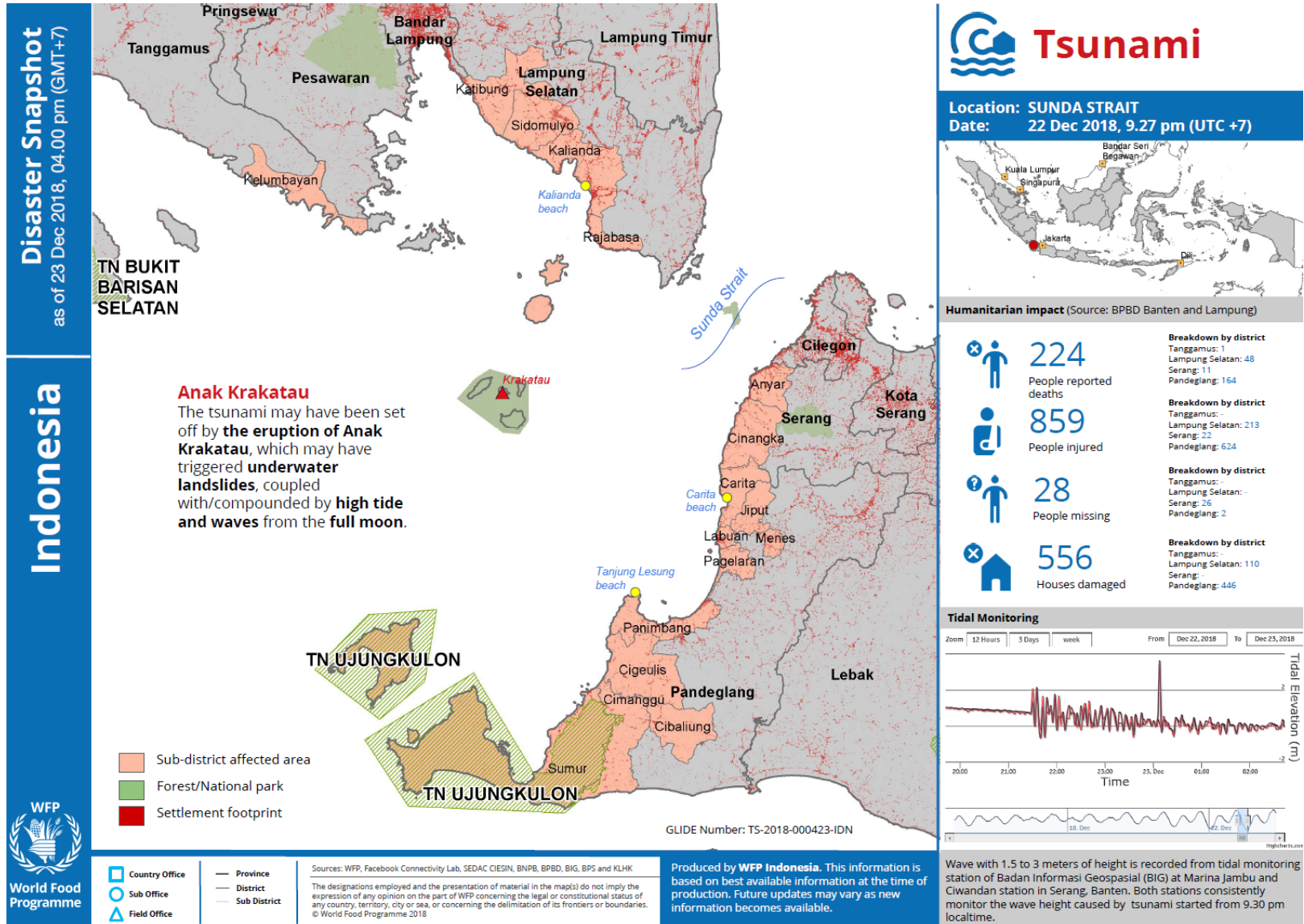


IMPACT OF THE DECEMBER 2018 INDONESIA TSUNAMI





IMPACT OF THE DECEMBER 2018 INDONESIA TSUNAMI AS OF 22 DECEMBER





IMPACT OF THE DECEMBER 2018 INDONESIA TSUNAMI AS OF 27 DECEMBER

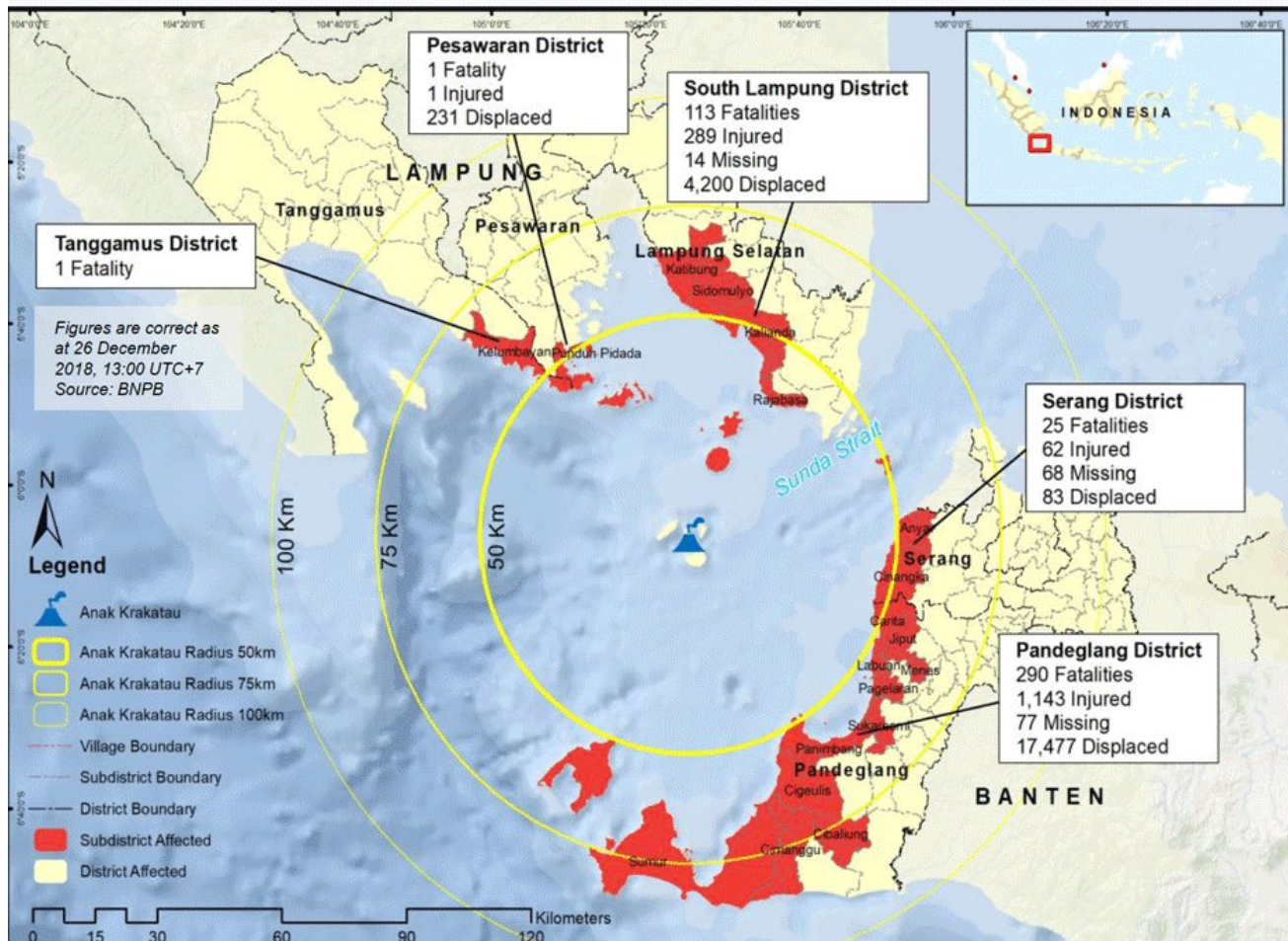
THURSDAY
27 DEC 2018
15:00 UTC+7

Sunda Strait Tsunami Banten and Lampung Provinces, Indonesia Flash Update No. 04

<http://adinet.ahacentre.org/reports/view/1383>



ONE ASEAN ONE RESPONSE



430
fatalities

159
missing

1,495
injured

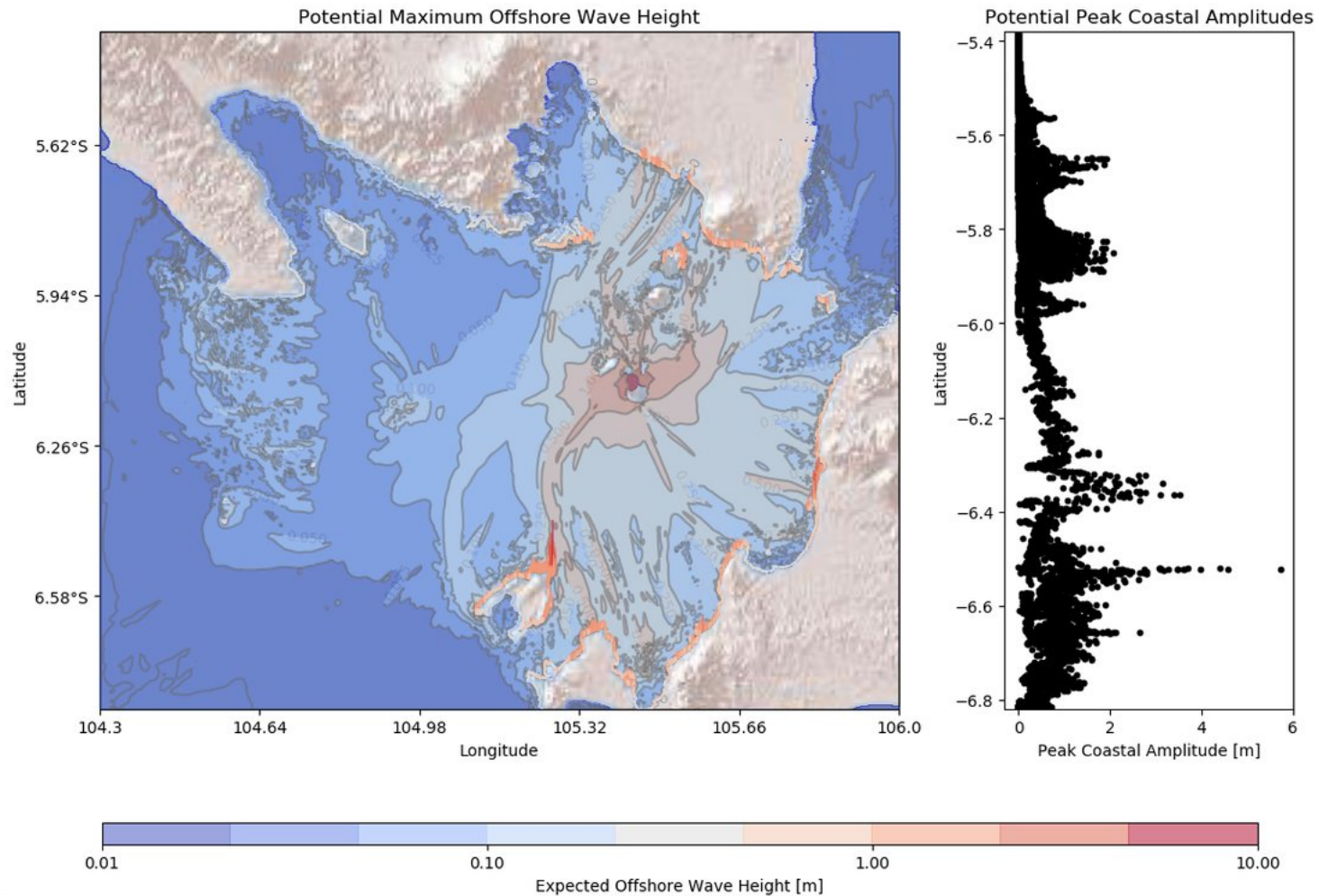
21,991
Displaced

Figures are correct as at 26
December 2018, 13:00
UTC+7



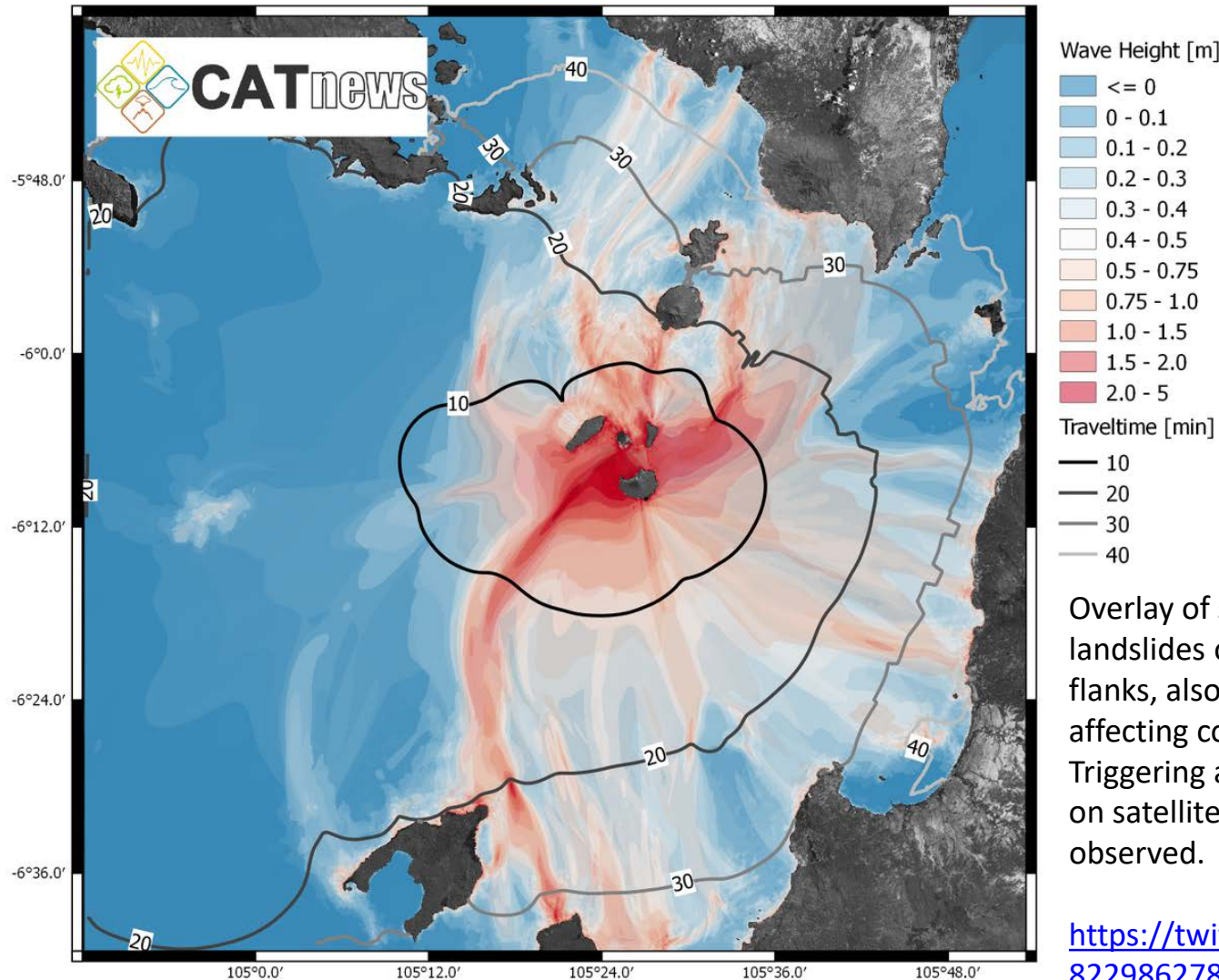
POTENTIAL DISASTER IMPACT: LANDSLIDE-TSUNAMI OFFSHORE INDONESIA

Potential Disaster Impact: Landslide-Tsunami offshore Indonesia
Dec 22, 2018, 14:00 UTC, Lat=-6.11, Lon=105.43





IMPACT OF THE DECEMBER 2018 INDONESIA TSUNAMI



Overlay of several different Krakatoa tsunami landslides on the south eastern and western flanks, also showing expected travel times affecting coasts of Banten, Indonesia. Triggering around 13:50-14:00 UTC, explosion on satellite and low frequency seismic signal observed.

<https://twitter.com/CATnewsDE/status/1076822986278273024>



IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI

As regards the impact on the built environment, the building stock of the affected beaches suffered non-structural and structural damage. Buildings are mainly classified to (a) wooden structures, (b) reinforced concrete buildings, (c) mixed types of structures with prevailing wooden elements and secondary concrete elements and (d) structures with light steel frame.

All structures founded along the beach front suffered heavy structural damage. More specifically, the wooden structures were washed away by the tsunami waves.

The RC structures suffered mainly heavy non-structural damage. Their infill walls of the ground floor were blown away due to the impact with tsunami waves, mobile objects and tsunami debris. Columns of the first floor were damaged due to the aforementioned impact. The damage observed in the first floor depends on the height of the tsunami waves, while the upper floor remained intact. However, many small RC buildings located along the beach front in the heavily tsunami-affected areas were also swept away. The tsunami washed away many of them, leaving only their concrete base and

buckled the remaining still standing columns.

The structures with light steel frame also suffered heavy structural damage with intense deformation of the frame and complete destruction. Similar damage was also observed in the mixed structures.

Due to the fact that the tsunami was generated during the night and without previous warning for evacuation, it reached the coastal areas without being noticed by anyone. The destructive power of the tsunami was enhanced by the already high tide in the area. A warning has been already issued by the Indonesian authorities for the high sea level during Christmas period and for probable abnormal tidal surges due to full moon.

The tsunami was a medium one, but caused large human losses and damage to buildings and infrastructures. This fact is attributed to the synergy of the tsunami generation during the night and the lack of warning among other aggravating factors including construction of buildings on the beach front and shallow sea bed morphology. This combination gave no chance for immediate evacuation and increased the resulted damage.



IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON MOBILE OBJECTS

Cars





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON MOBILE OBJECTS

Cars





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON MOBILE OBJECTS

Vessels and boats are washed away, destroyed or moved to higher elevation



→ Arrows indicate direction of tsunami water flow



IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON WOODEN BUILDINGS

Many wooden houses were swept away within areas struck particularly hard. The tsunami washed away many of them, leaving only their concrete base.





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON WOODEN BUILDINGS

All sea front wooden structures were washed away by the incoming tsunami waves resulting in sites of debris accumulation along the affected coastal area





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON WOODEN STRUCTURES

All wooden structures along the beach were washed away by the incoming tsunami waves resulting in destruction





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON REINFORCED CONCRETE BUILDINGS



Their infill walls of the ground floor are blown away due to impact with tsunami waves, mobile objects and tsunami debris. Columns of the first floor are damaged due to impact with tsunami waves, mobile objects and tsunami debris. The damage observed in the first floor depends on the height of the tsunami waves. The upper floor of the buildings remained intact.

Arrows indicate the direction of tsunami water flow





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON REINFORCED CONCRETE BUILDINGS





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON REINFORCED CONCRETE BUILDINGS





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON REINFORCED CONCRETE BUILDINGS



Arrows indicate direction of tsunami water flow



IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON RC BUILDINGS

Many sea front RC buildings were also swept away. The tsunami washed away many of them, leaving only their concrete base and buckled the remaining still standing columns.





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON SEA FRONT WALLS





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON COASTAL VEGETATION

Uprooted palm trees due to tsunami on the sand. indicator of the advancing direction of tsunami.





IMPACT OF THE VOLCANO-TRIGGERED TSUNAMI ON COASTAL MORPHOLOGY

Boulders were either detached from and emplaced on shallower parts of the sea bed close to the affected beaches or displaced for a small distance.

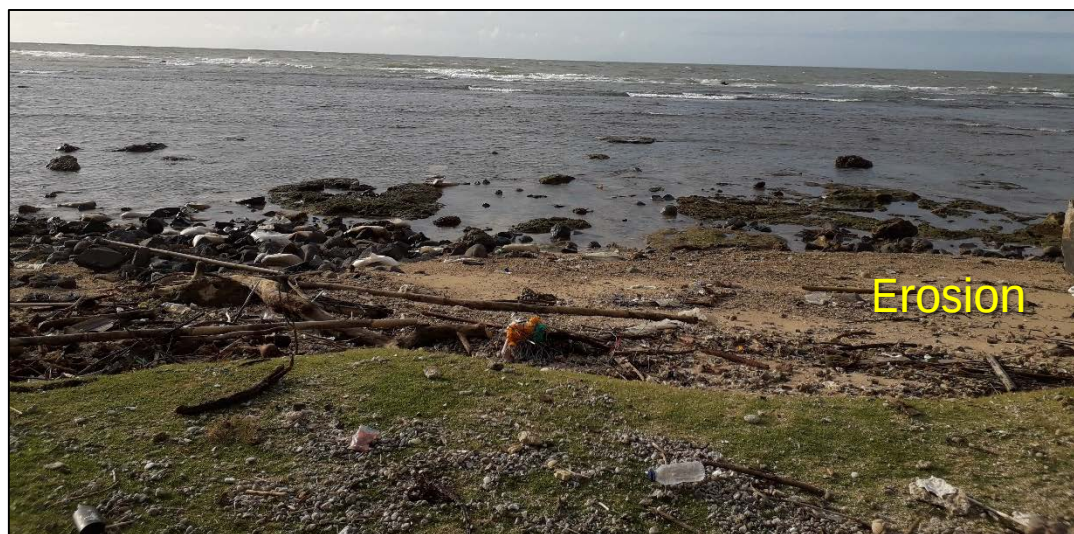




GEOMORPHOLOGICAL CHANGE AND COASTAL EROSION DUE TO THE TSUNAMI

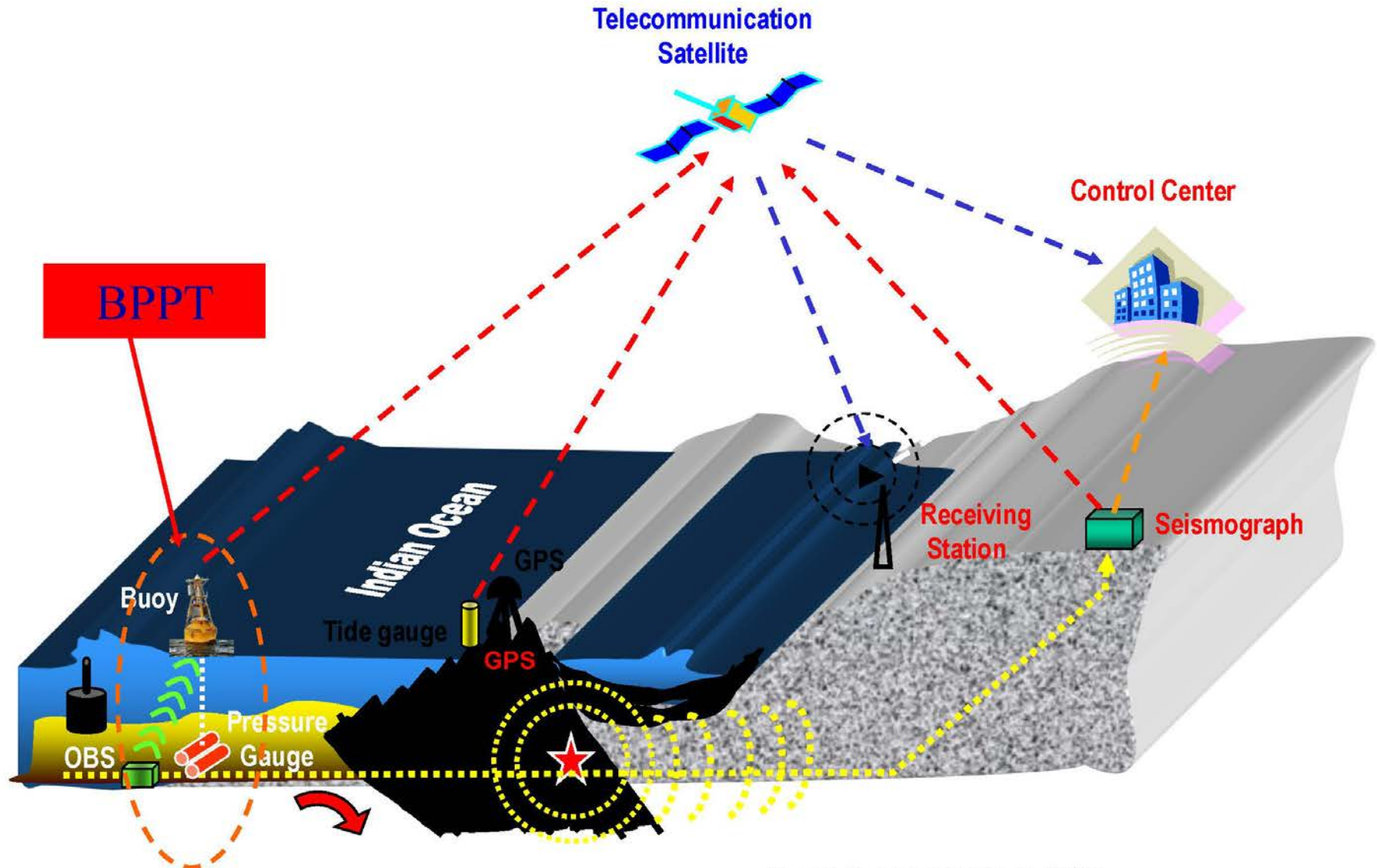
Beach erosion was induced due the tsunami.

Waves removed beach sand about 1 m vertically and 20 to 30 meters wide and deposited it further inland.



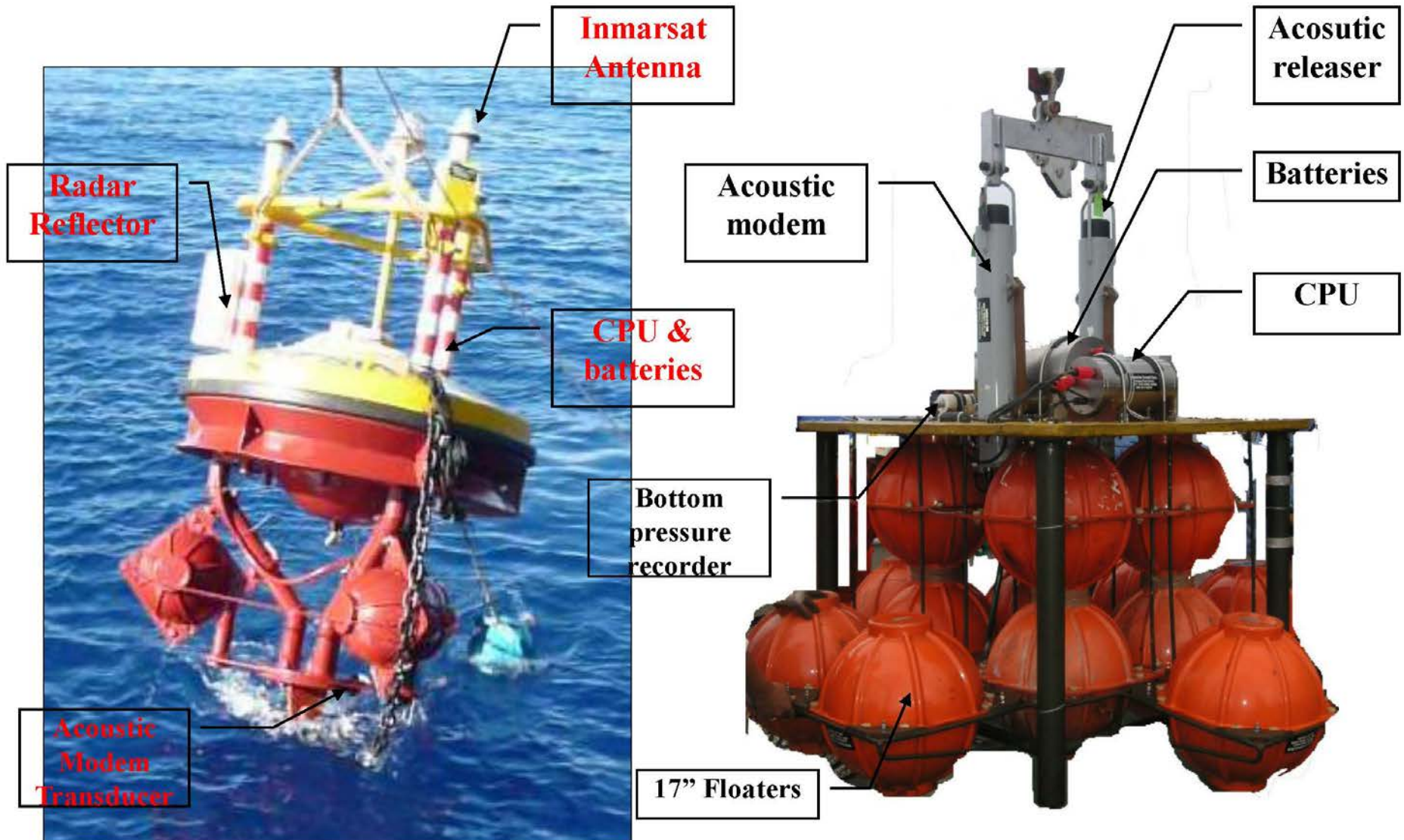


DESIGN OF THE INDONESIAN TSUNAMI EARLY WARNING SYSTEM



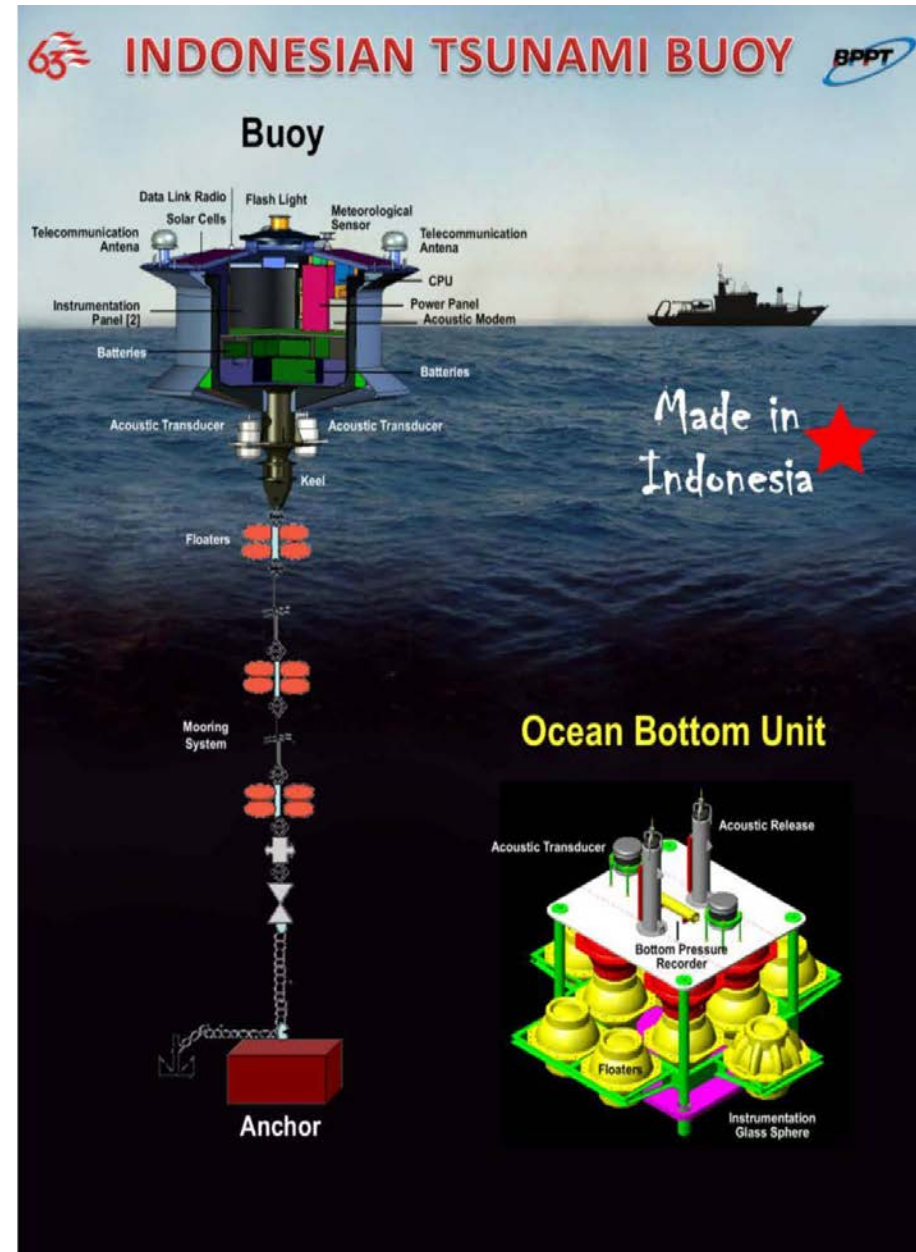


2006 BUOY AND OBU DESIGN 1st GENERATION SERIES



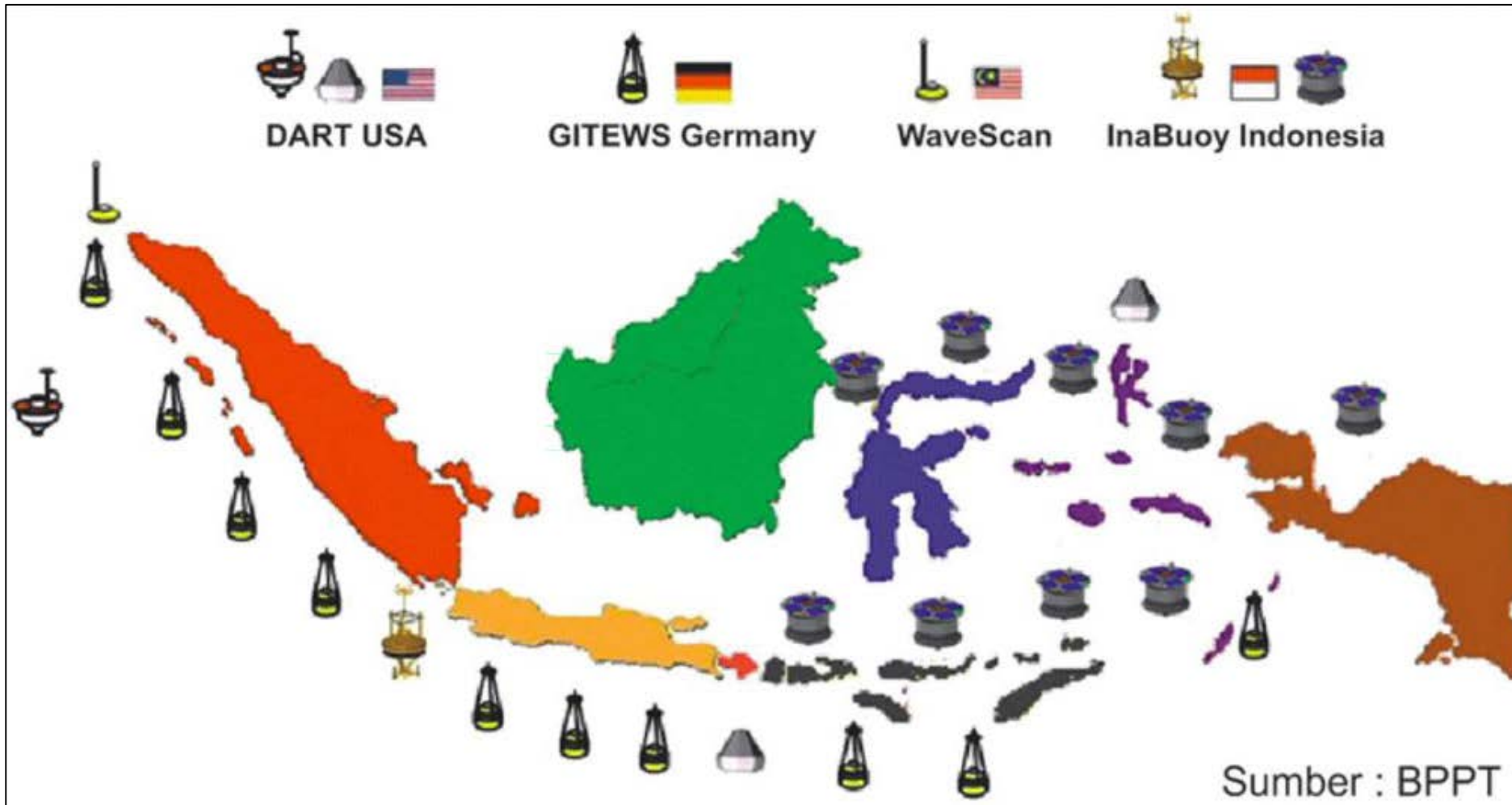


2007-2008 BUOY AND OBU DESIGN 2nd GENERATION SERIES



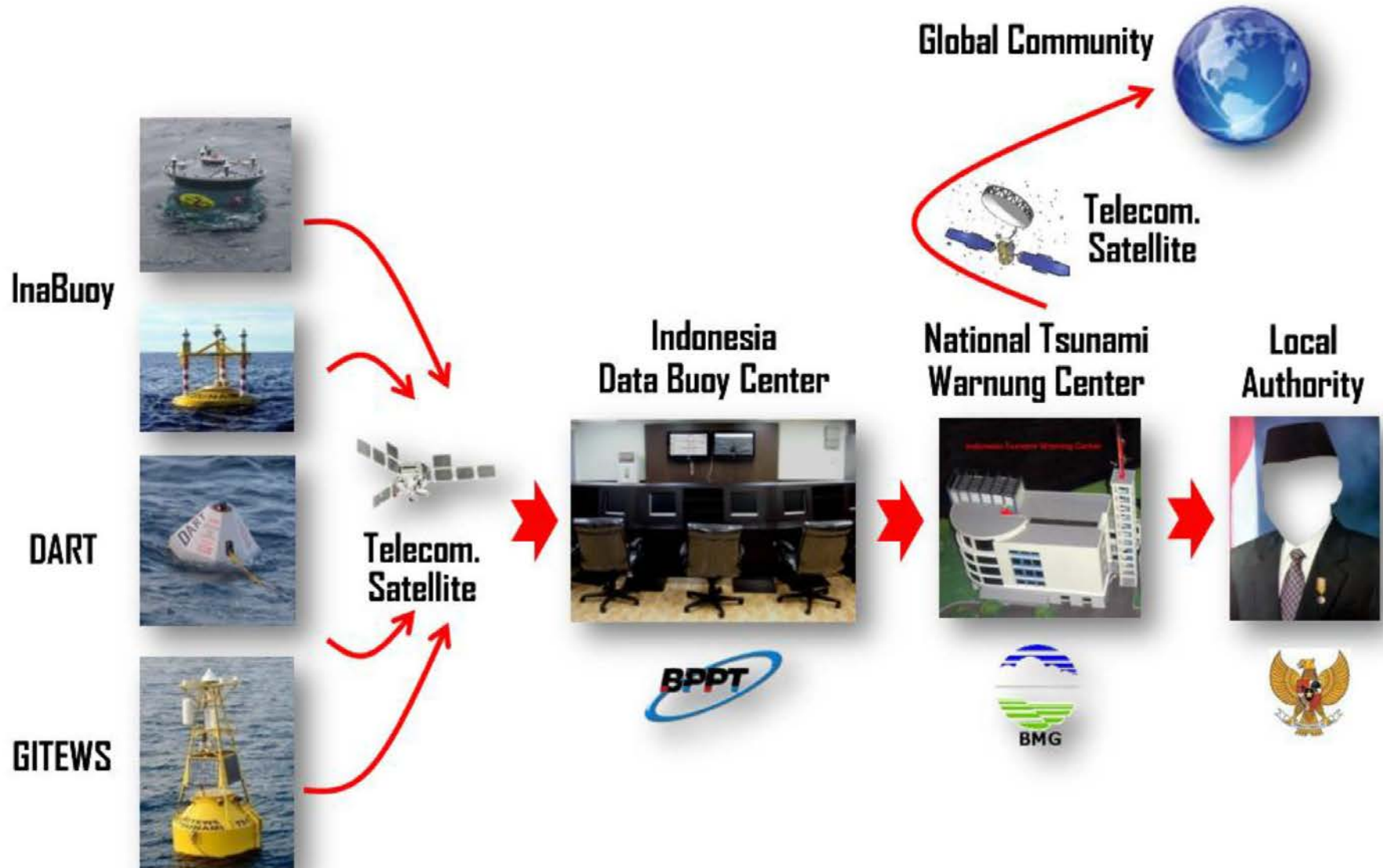


TSUNAMI BUOY ARRAY IN INDONESIAN WATERS



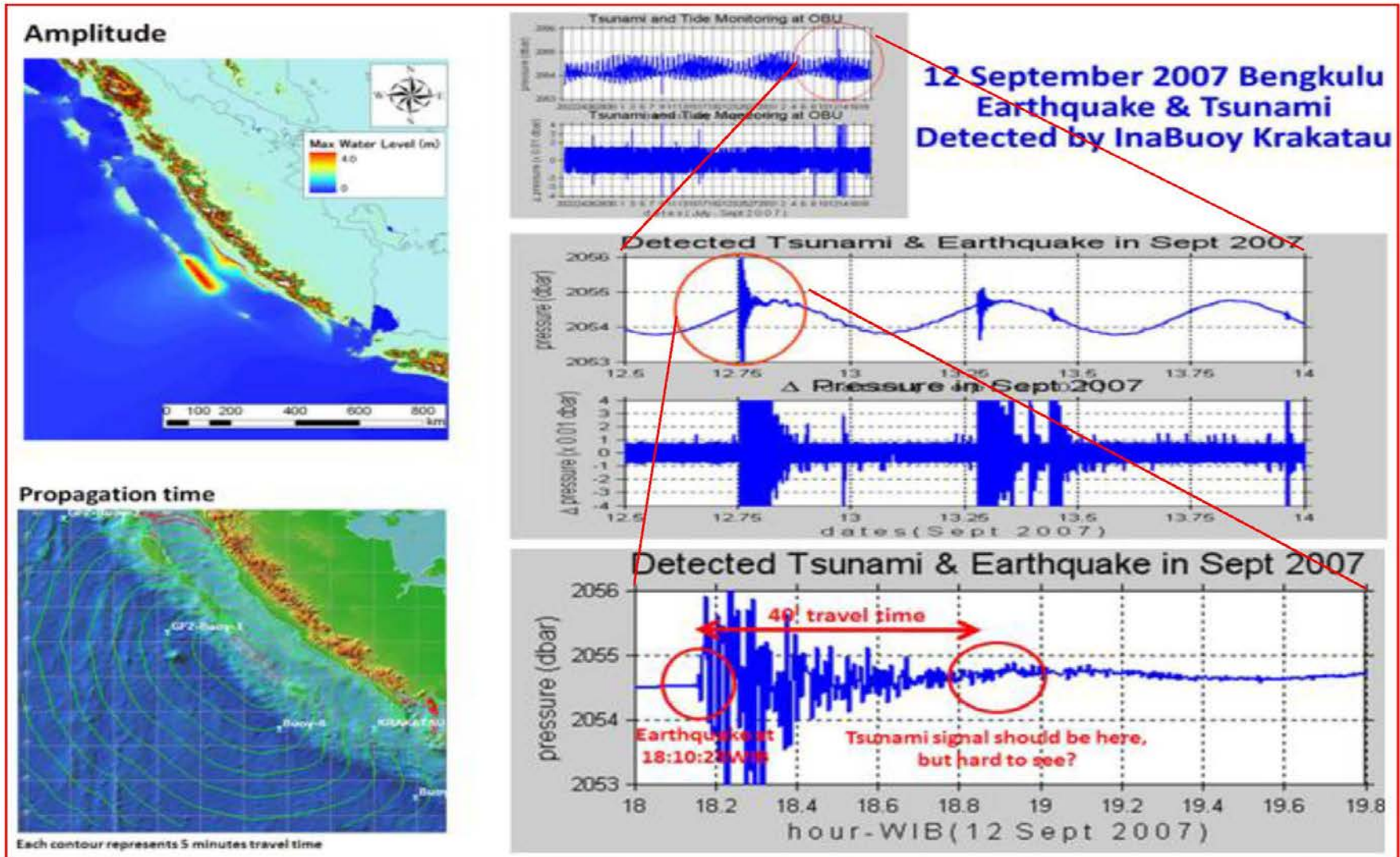


BUOY DATA FLOW



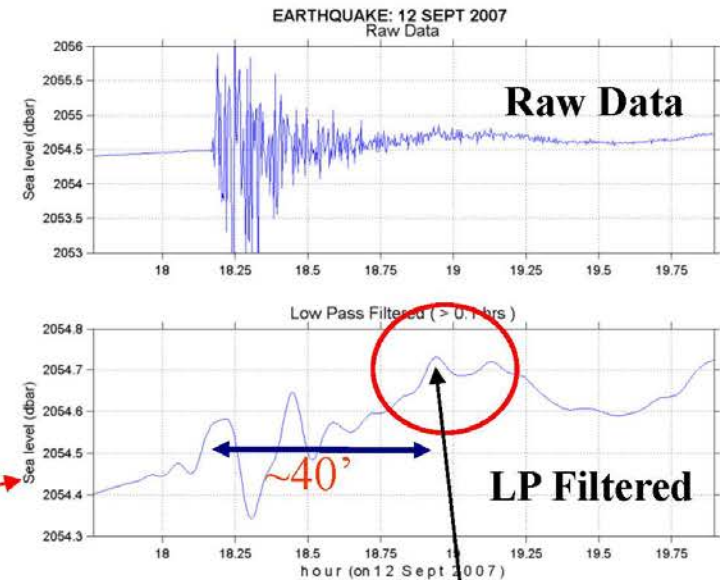
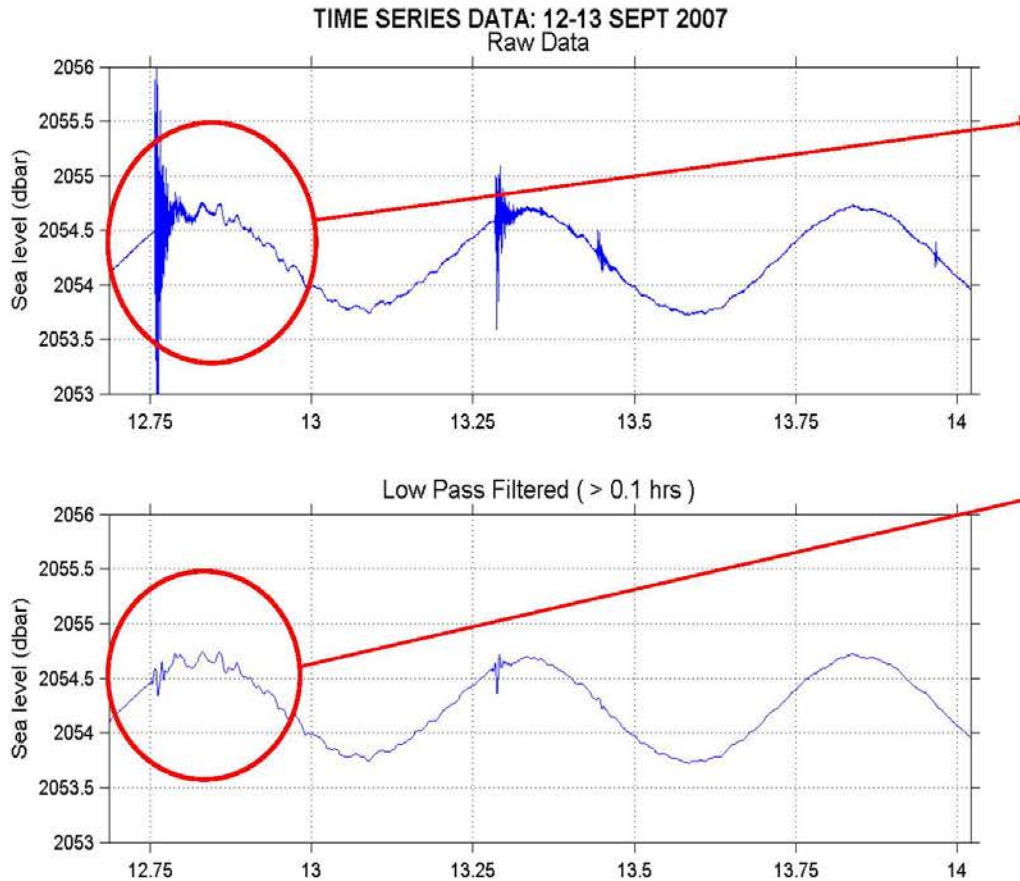


BENGKULU EARTHQUAKE AND TSUNAMI, 12 SEPTEMBER 2007 SUCCESSFULLY DETECTED BY THE TSUNAMI BUOY ARRAY





EARTHQUAKE AND TSUNAMI ON 12 SEPTEMBER 2007 SUCCESSFULLY DETECTED BY THE INDONESIAN KRAKATAU TSUNAMETER

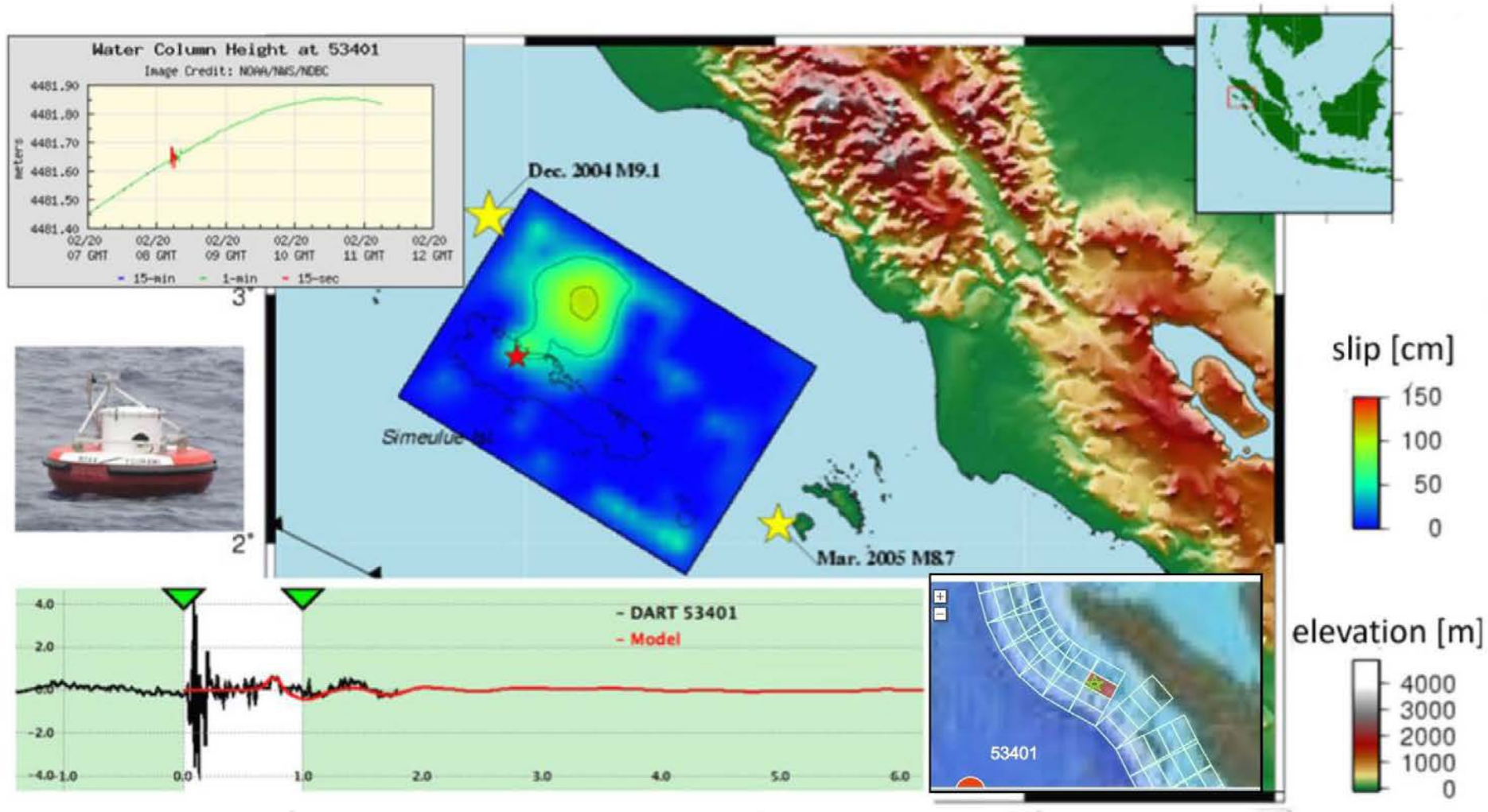


detected Tsunami signals?

Predictive Filtering and
detiding algorithms are
required in real time !

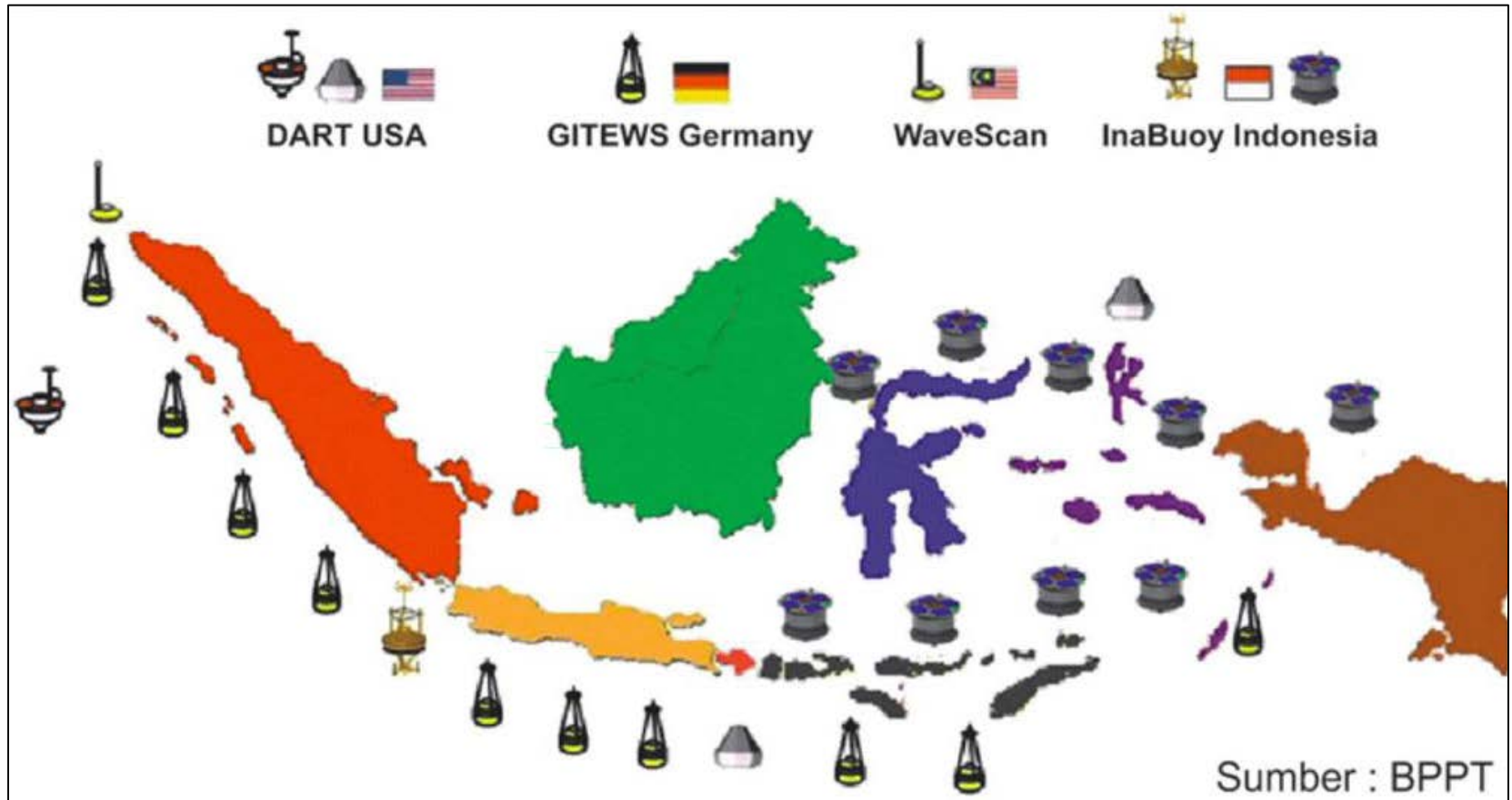


EARTHQUAKE AND TSUNAMI ON 20 FEBRUARY 2008 SUCCESSFULLY DETECTED BY THE TSUNAMI BUOY ARRAY





TSUNAMI BUOY ARRAY IN INDONESIAN WATERS NO OPERATING SINCE 2012



Tsunami detecting and early warning systems in Indonesian waters have not been operating since 2012. Vandalism, limited budget, technical damage have caused no current tsunami system. There is need to be rebuilt in order to strengthen the Indonesian Tsunami Early Warning System and to protect the Indonesian population. Indonesia must build an early warning system able to detect underwater landslides and volcanic eruptions.



