NEAR AND FAR-FIELD EFFECTS OF TSUNAMIS GENERATED BY THE PAROXYSMAL ERUPTIONS, EXPLOSIONS, CALDERA COLLAPSES AND MASSIVE SLOPE FAILURES OF THE KRAKATAU VOLCANO IN INDONESIA ON AUGUST 26-27, 1883

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ABSTRACT

The paroxysmal phases of Krakatau's volcanic activity on August 26-27, 1883, included numerous submarine Surtsean (phreatomagmatic) eruptions, three sub air Plinian eruptions from the three main craters of Krakatau on Rakata island, followed by a fourth gigantic, sub air, Ultra-Plinian explosion. Landslides, flank failures, subsidences and a multiphase massive caldera collapse of the volcano - beginning near the Perbowetan crater on the northern portion of Rakata and followed by a collapse of the Danan crater - occurred over a period of at least 10 hours. The first of the three violent explosions occurred at 17: 07 Greenwich time (GMT) on August 26. The second and third eruptions occurred at 05:30 GMT and at 06:44 GMT on August 27. Each of these events, as well as expanding gases from the submarine phreatomagmatic eruptions, lifted the water surrounding the island into domes or truncated cones that must have been about 100 meters or more in height. The height of the resulting waves attenuated rapidly away from the source because of their short periods and wavelengths. It was the fourth colossal explosion (VEI=6) and the subsequent massive f lank failure and caldera collapse of two thirds of Rakata Island, at 10:02 a.m., on August 27 that generated the most formidable of the destructive tsunami waves. A smaller fifth explosion, which occurred at 10:52 a.m., must have generated another large water cone and sizable waves. The final collapse of a still standing wall of Krakatau - which occurred several hours later at 16:38, generated additional waves.

The near field effects of the main tsunami along the Sunda Strait in Western Java and Southern Sumatra, were devastating. Within an hour after the fourth explosion/caldera collapse, waves reaching heights of up to 37 m (120 feet) destroyed 295 towns and villages and drowned a total of 36,417 people. Because of their short period and wavelength, the wave heights attenuated rapidly with distance away from the source region. It took approximately 2.5 hours for the tsunami waves to refract around Java and reach Batavia (Jakarta) where the only operating tide gauge existed. Waves

of 2.4 meters in height were recorded - but with an unusually long period of 122 minutes. The long period is attributed to modification due to resonance effects and did not reflect source characteristics. The tsunami travel time to Surabaya at the eastern part of Java was 11.9 hours. The reported wave was only 0.2 meters.

The far field effects of the tsunami were noticeable around the world, but insignificant. Small sea level oscillations were recorded by tide gauges at Port Blair in the Andaman Sea, at Port Elizabeth in South Africa, and as far away as Australia, New Zealand, Japan, Hawaii, Alaska, the North-American West Coast, South America, and even as far away as the English Channel. It took 12 hours for the tsunami to reach Aden on the southern tip of the Arabian Peninsula, about 3800 nautical miles away. The wave reported at Aden, at Port Blair and at Port Elizabeth, represents the actual tsunami generated in the Sunda Strait. There were no land boundaries on the Indian Ocean side of Krakatau to prevent the tsunami energy from spreading in that direction. The tsunami travel time of a little over 300 nautical miles per hour to Aden appears reasonable. However, it is doubtful that the waves, which were reported at distant locations in the Pacific or in the Atlantic Ocean, represented the actual tsunami generated in the Sunda Strait. Very little, if any at all, of the tsunami energy could have escaped the surrounding inland seas to the east of the Sunda Strait. Most probably, the small waves that were observed in the Pacific as well as in the Atlantic were generated by the atmospheric pressure wave of the major Krakatoa explosion, and not from the actual tsunami generated in the Sunda Strait. The unusual flooding, which occurred at the Bay of Cardiff, in the U.K., was caused by atmospheric coupling of the pressure wave from the major Krakatau eruption.

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INTRODUCTION

The effects of the volcanic explosions and collapses of the volcano of Krakatau in Indonesia on August 26-27, 1883, including the effects of its destructive tsunami, were extensively reported in early scientific reports based on geological surveys and data collected in the affected area (Verbeek, 1884; Fuchs, 1884; Warton & Evans, 1888). Most of the original publications include descriptive documentation of the tsunami near field effects in the Sunda Strait and elsewhere in Indonesia, with speculations as to the tsunami source mechanism. Analysis of the geological data collected by early and subsequent surveys resulted in publications that further documented the caldera collapse and provided additional evaluation as to what occurred in 1883 and about tsunamis generated from subsequent eruptions of Anak Krakatau (Montessus de Ballore, 1907; Escher, B.G., 1919, 1928; Stehn, 1929; Wilson et al 1973;)

Additional descriptions of the tsunami effects - based on original and subsequent references – were included in historical catalogs of earthquakes and tsunamis (Milne, 1912; Svyatlowski, 1957, Kawasumi, 1963; Heck, 1947; Imamura, 1949; Iida et al., 1967). Similarly, water level disturbances at tide gauges from the great explosion were extensively reviewed and evaluated (Ewing & Press, 1955). Subsequent computations of the tsunami travel time and the modeling of the tsunami were undertaken, using a point tsunami source and a simplified tsunami generation mechanism (Nomanbhoy & Satake 1997). Subsequent publications drew comparisons and analogies between Krakatau's explosion/collapse tsunami mechanism with that of the multi-phase explosions and collapses of the volcano of Santorin in the Bronze Age (Pararas-Carayannis, 1973, 1974, 1983, 1992).

Based on original surveys and a very extensive review of the geologic data in the scientific literature, a comprehensive publication further described Krakatau's eruption and its effects (Simkin & Fiske, 1983). The accuracy of its historical tsunami data was further verified by a review of original documents – some translated from Dutch, German and French publications – prior to the above publication and for corrections of earlier historical catalogs of tsunamis (Pararas-Carayannis, 1983)

The atmospheric pressure effects of the Krakatau's explosion were also researched and documented (Hirota, 1983). Additional tsunami descriptions were provided in numerous other publications (Anon., 1883; Whitney, 1992; Simkin & Siebert, 1994; Decker & Hadikusumo, 1961; Furneaux, 1964; Decker & Decker, 1989; Sea Frontiers, 1971). Over the years, numerous articles in magazines and newspapers about the1883 Krakatau disaster and its destructive tsunami have fascinated and continue to fascinate readers. Similarly, museums and Internet web sites have provided extensive descriptions and bibliographies.

More recent papers have evaluated the tsunami generation mechanisms for different types of volcanoes with varying eruption intensities, have assessed the risk of postulated mega tsunami generation from massive edifice failures of island stratovolcanoes such as Krakatau, Santorin, Piton de la Fournaise Cumbre Vieja, and Kilauea (Pararas-Carayannis, 2002a,b).

The present study is part of an ongoing investigation of tsunami source mechanisms from large-scale sub aerial and submarine volcanic and non-volcanic, mass waste processes. It examines briefly only the kinematic processes of flank failure and caldera collapses during the paroxysmal phases of Krakatau's eruption on August 26-27, 1883, comments on specific source characteristics and mechanisms of tsunami generation resulting from such mass waste of volcanic edifice structure, and summarizes the near and far-field tsunami effects – including the generation of atmospherically-induced sea level disturbances at great distances from the source region.

GEOLOGIC SETTING

Krakatau (Krakatoa) is one of the volcanoes of the Sunda volcanic arc in Indonesia, located in the Sunda Strait, at 16.7 S. Latitude and 105.4 E. Longitude, 40 km off the west coast of Java. The stratovolcano was formed by the subduction of the Indian-Australia Plate under the Eurasian Plate. Great volcanic eruptions have occurred in this region in the distant geologic past. A mega-colossal volcanic explosion/collapse during the Quaternary period of the Ice Age, approximately 75,000 years ago, devastated the center of the island of Sumatra and created a 100 km long caldera, now the site of Lake Toba. The volume of tephra discharge from this massive volcanic eruption is estimated at 2,000 cubic km. The massive 1815 Ultra-Plinian eruption/explosion of the Mount Tambora volcano ejected between 100 and 200 cubic kilometers of tephra.

BRIEF HISTORY OF KRAKATA'S VOLCANIC ACTIVITY AND TSUNAMI GENERATION

At its peak, the island of Rakata, which the volcano of Krakatau had formed, had reached a height of 790 m (2,600 ft.) above sea level. According to ancient Japanese scriptures, the first known super-colossal eruption of Krakatau occurred in the year 416 A. D. – Some have reported it to occur in 535 A.D. The energy of this eruption is estimated to have been about 400 megatons of TNT, or the equivalent of 20,000 Hiroshima bombs. This violent early eruption destroyed the volcano, which collapsed and created a 7 km (4-mile) wide submarine caldera. The remnants of this earlier violent volcanic explosion were the three islands of Krakatau, Verlaten and Lang (Rakata, Panjang, and Sertung). Undoubtedly the 416 A.D. eruption/explosion/collapse generated a series of catastrophic tsunamis, which must have been much greater than those generated in 1883. However, there are no records to document the size of these early tsunamis or the destruction they caused.

Subsequent to the 416 A.D. eruption and prior to 1883, three volcanic cones of Krakatau and at least one older caldera had combined again to form the island of Rakata. The volcanic cones on the island were aligned in a north-south direction. The northernmost was called Poeboewetan and the southernmost was called Rakata. Overall approximate dimensions of the island were 5 by 9 Kilometers.

A long period of relative inactivity of Krakatau was interrupted by a moderate eruption that occurred between May 1680 and November 1681. This activity destroyed all the lush vegetation that had grown on the island. Large quantities of rock, pumice, and ash fell into the sea. Undoubtedly, volcanic edifice mass waste, subsidence and partial flank failure events associated with this activity, generated large local tsunamis. However, the geomorphology of the island was not altered significantly. Thus, prior to the great 1883 eruption, Krakatau was the remnant of the older volcano that had not erupted for 200 years.

The great 1883 eruptions, explosions, mass waste and collapse events of Krakatau generated the catastrophic tsunamis along the Sunda Strait. Subsequent local tsunamis in the Sunda Strait were generated by the 1927 and 1928 eruptions of the new volcano of Anak Krakatau (Child of Krakatau) that formed in the area. Although large tsunamis were generated from these recent events, the heights of the waves attenuated rapidly away from the source region, because their periods and wavelengths were very short. There was no report of damage from these more recent tsunamis in the Sunda Strait.

CHRONOLOGY OF EVENTS PRIOR TO KAKATAU'S PAROXYSMAL PHASE

As mentioned, following about 200 years period of inactivity, Krakatau became active again in early 1883 when a large earthquake struck the area. There was subsequent increase in seismic activity. On May 20, 1883 Krakatau begun to erupt again. The initial explosive eruptions could be heard 160 km away. Steam and ash could be seen rising 11km above the summit of the volcano. Most of the activity was from the 3 main vents – Perboewatan being the most active. The eruptions continued with varying degrees of severity to August – producing only gas, steam and ashes. During that period the Danan vent got progressively wider because of collapses. By August 11, 1883. Three major vents of Krakatau were actively erupting. Eleven other vents were ejecting smaller quantities of steam, ash and dust.

CHRONOLOGY OF EVENTS DURING KRAKATAU'S PAROXYSMAL PHASE

The paroxysmal phase of Krakatau's eruption took place in less than two days – on August 26 and 27, 1983 – with remarkably few reported earthquakes. This final phase included numerous submarine Surtsean (phreatomagmatic) eruptions, three sub aerial Plinian eruptions from the three main craters, followed by a fourth gigantic, sub aerial, ultra-Plinian explosion, mass waste, flank failures and massive caldera collapse.

The first of the four violent explosions begun with extraordinary intensity at 17: 07 Greenwich time (GMT) on August 26, 1883 (27 August local date). Subsequently, eruptions of lesser magnitude became more frequent, occurring on the average every 10 minutes. The first and subsequent smaller explosions sent huge volumes of airborne tephra that completely blocked out the sun and brought darkness to the Sunda Straits. A black cloud of smoke rose 27 kilometers (17 miles) above the volcano and was seen and reported by sailors on a ship, 120 km away. At the time, a plug of solid lava apparently blocked Krakatau's central vent. Underneath it pressure was rapidly building up. Subsequently, there was a partial caldera collapse which increased Krakatau's Perboewatan crater to approximately 1,000 meters in diameter and its average depth to about 50 meters. Also, several submarine Surtsean (phreatomagmatic) eruptions and partial flank collapses of the island must have occurred during this initial period. Probably, these continued intermittently during the following 10-hour period.

The second and third of Krakatau's violent explosions occurred at 05:30 GMT and at 06:44 GMT on August 27, 1883, respectively. Finally, at 10:02 (GMT) on August 27, the fourth paroxysmal eruption/explosion blew away the northern two-thirds of Rakata Island. Almost instantaneously this explosion was followed by a very substantial collapse of the unsupported volcanic chambers of Krakatau, thus forming a huge underwater caldera.

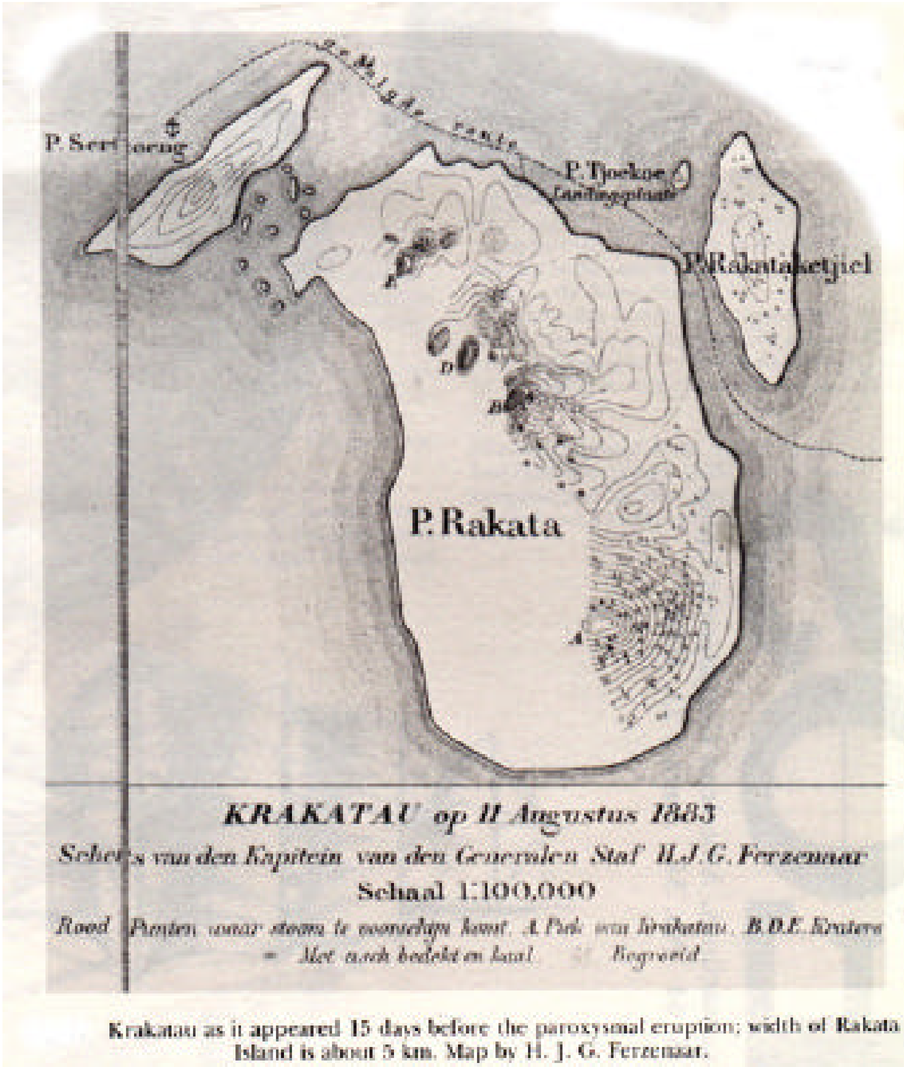
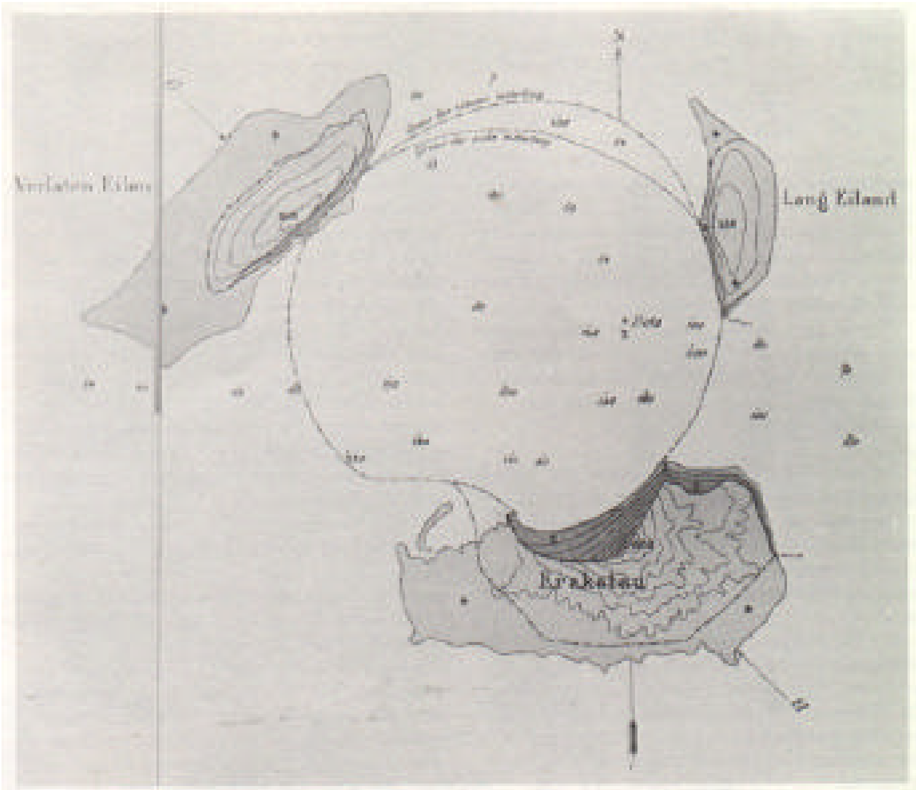


Figure 1. Schematic of Rakata Island prior to Krakatau's 1883 paroxysmal eruptions (After H. J. G. Ferzenaar, included in Verbeek)

A smaller fifth explosion occurred at 10:52 a.m. on August 27. The final collapse of a still standing wall of Krakatau – occurred several hours later, at 16:38. The entire northern part of Rakata Island had disintegrated completely. The combined explosions and collapses of the volcano destroyed a good part of the island. Its remnant is now known as the island of Krakatau.



Krakatau 7 weeks after the paroxysm; diameter of caldera is about 7 km. Map by R. D. M. Verbeek.

Figure 2. Schematic of Krakatau after the paroxysmal phase (After R. D. M. Verbeek, 1884)

MAGNITUDE OF THE 1883 ERUPTIONS/EXPLOSIONS OF THE KRAKATAU VOLCANO

The fourth explosion of Krakatau at 10:02 (GMT) on August 27 resulted in the ejection of 15-20 cubic km of material. At least 2 cubic Km of the finer material was blown to a height of 27 Km. The event was assigned a Volcanic Explosivity Index of VEI=6 – which rates as “colossal”. To be assigned a VEI rating of 6, a volcanic eruption must have a plume height over 25 km and a displacement volume ranging between 10 and 100 km3. Eruptions of this size occur only once every few hundred years on earth.

The total thermal energy released by the four main events of the 1883 eruptions is estimated to be equivalent to 200 megatons of TNT. Most of this energy was released by the fourth paroxysmal explosion, which is estimated to be the thermal energy release of about 150 –175 megatons of TNT, or the equivalent of about 7,500 – 8,750 Hiroshima atomic bombs (the Hiroshima bomb released about 20 kilotons of thermal energy).

Krakatau’s tremendous explosions were heard throughout the area and beyond, over 1/3 rd of the earth’s surface. They were heard as far away as 3,540 kilometers (2,200 miles) away in Australia, and even as far away as Rodrigues Island which is 4,653 km (2,908 miles) away to the west-southwest, in the Indian Ocean, about 1,000 miles (1,600 km) east of Madagascar. People on

Rodrigues Island described the sounds to be like the distant roar of firing canons. The sounds continued at intervals of three to four hours during the night of August 26th.

SOURCE DIMENSIONS AND MECHANISMS OF TSUNAMI GENERATION

The 1883 eruption of Krakatau provides the best understanding of the tsunamigenic potential from mass failures and collapses of island volcanoes. It is believed that not one but several tsunamis were generated as a result of several events that occurred during Krakatau's paroxysmal phase. The following source dimensions and mechanisms of tsunami generation are inferred from examination of historical records, chronology of events, underwater topography of Krakatau's post 1883 caldera and geological evidence. The 1927 birth of Anak Krakatau volcano (Stern, 1929a) in the caldera of Krakatau altered significantly the underwater topography. However, observations from Strombolian intensity eruptions of Anak Krakatau in 1928 shed additional light on the mechanisms of tsunami generation from volcanic explosions.

Mechanisms: Violent Plinian and Ultra-Plinian eruptions/explosions, submarine phreatomagmatic activity and other associated processes such as atmospheric shock waves, magmatically-induced earthquakes, gravitational settling, sudden coastal subsidence, rock falls, landslides, flank failures and massive caldera collapses, are some of the kinematic mechanisms by which several destructive local tsunamis were generated during Krakatau's paroxysmal phase on August 26 and 27, 1983. Geologic evidence and the chronology of events support the following sequential tsunami generation mechanisms.

During the first 10 hours of Krakatau's paroxysmal eruptive phase, local tsunamis were generated in the immediate area primarily from numerous landslides, rock falls, flank failures, subsidences, falling ejecta, submarine phreatomagmatic eruptions and the atmospheric shock waves associated with the first three explosions. Also, during this period, sub aerial, multiphase collapses of the volcanic vents occurred on Rakata Island. However, none of these nor the major caldera collapse which begun near the Perbowetan crater on the northern portion of the island or the subsequent partial collapse of the Danan crater, contributed to tsunami generation. These collapses occurred above sea level.

Tsunami Generation During the Early Paroxysmal Phase: The first three explosions ejected material primarily upwards and did not displace much water to generate a large tsunami. Other concurrent mass waste phenomena and falling ejecta must have contributed to the generation of large waves. These waves had relatively short periods and wavelength and their heights attenuated rapidly as they propagated away from the source region. However, the atmospheric shock waves from these explosions and concurrent phreatomagmatic eruptions must have generated larger waves. The expanding gases from submarine phreatomagmatic activity must have lifted the water surrounding the island into domes or truncated cones that, at times, could have been as much as a 30-50 meters in height. Also, the height of the waves that were thus generated attenuated very rapidly away from the source area because of the limited source dimensions and the resulting short periods and wavelengths. This conclusion is supported by observations of the tsunami waves observed during the 1928 eruptions of Anak Krakatau – the Son of Krakatau – that subsequently formed in the area.

Tsunami Generation During Final Paroxysmal Phase: The fourth colossal paroxysmal eruption/explosion which occurred at 10:02 (GMT) on August 27, blew away the northern two-thirds of Rakata island, resulting in the ejection of about 15-20 cubic km of material, and generating the major destructive tsunami in the Sunda Strait. In spite of limited observations and data, it is very likely that the destructive tsunami occurred in accordance to the following sequential scenario.

Most of the force of the fourth explosion was also directed upwards, so there was no significant contribution to tsunami generation. However, the atmospheric shock wave was much more powerful than those of the earlier explosions. Also greater was the concurrent submarine phreatomagmatic activity. Expanding gases from such activity must have lifted the water surrounding the island into a dome or a truncated cone, rounded at the top and forming an acute angle with the surface of the water. The water cone thus raised must have been about100 meters or more in height. Substantial waves of short period were generated but attenuated rapidly away from the source. The waves thus generated were more significant than those generated during the earlier phase of the paroxysmal activity. Supporting this scenario are the previously mentioned observations of wave generation during eruptions of the Anak Krakatau volcano.

Between January 12-20, 1928 eruptions of this new volcano generated water cones with heights of up to 26 meters which were photographed from Lang island. A subsequent eruption on January 24, 1928 generated a water mass of cylindrical shape. The waves were generated from Strombolian eruptions that lacked the intensity of the 1883 Plinian and super Plinian eruptions of Krakatau. The 1928 waves were sizeable but attenuated rapidly because of short periods and wavelengths.

Following the fourth eruption/explosion of the 1883 paroxysmal phase of Krakatau, additional waves were generated in the immediate area from the falling pyroclastics and the large blocks of pumice. These, too, were of extremely short periods and wavelengths and did not contribute significantly to tsunami energy propagation away from the source. Most probably the waves from falling pyroclastics created standing waves and a chaotic sea surface in the immediate area. The larger waves traveling in the same direction away from the source region quickly sorted out according to their periods and added to their heights.

Immediately following the fourth paroxysmal explosion of Krakatau, there must have been several successive massive flank failures on all sides of the volcano. The waves thus generated were sizeable but also of short period and wavelength. However within minutes after the fourth explosion, what was left of Krakatau’s basaltic peak begun to collapse into the volcano’s unsupported magmatic chambers resulting in the large depression of the sea floor which created the eastern branch of the 1883 submarine caldera. It was this massive caldera collapse and the associated flank failures that generated the major catastrophic tsunami in the Sunda Strait. A possible second explosion and caldera collapse contributed to the generation of an additional tsunami.

Tsunami Generation After the Major Paroxysmal Phase : What is concluded from the above is that the total engulfment and collapse of Krakatau did not occur as a single event. According to Verbeek (1894), fifty minutes after the major explosion, at 10:52 a.m., there was another severe detonation that was heard at great distance. This fifth explosion appears to have been primarily hydromagmatic and is not known to be associated with additional volcanic collapse. However, this event must have also generated another large, truncated cone of water and sizable waves. When waves form this subsequent event reached the nearest shores in the Sunda Strait about fifty minutes later, they were indistinguishable from the waves of the earlier destructive tsunami.

Also, the final collapse of a still standing wall of Krakatau which occurred several hours later at 16:38, must have generated additional tsunami waves of short wavelegth and period – also indistinguishable from the earlier major destructive tsunami. Given the catastrophic magnitude of the earlier tsunami waves that followed the 10:02 explosion, waves generated by both earlier and subsequent events were not noticed. The only tide gauge that operated in Batavia was too far to record these smaller tsunamis as separate discreet events. The small sea level disturbances that are evident on the earlier Batavia tide gauge record may have been caused by the atmospheric shock waves of the volcanic explosions, rather by the short period tsunami waves which were probably filtered out.

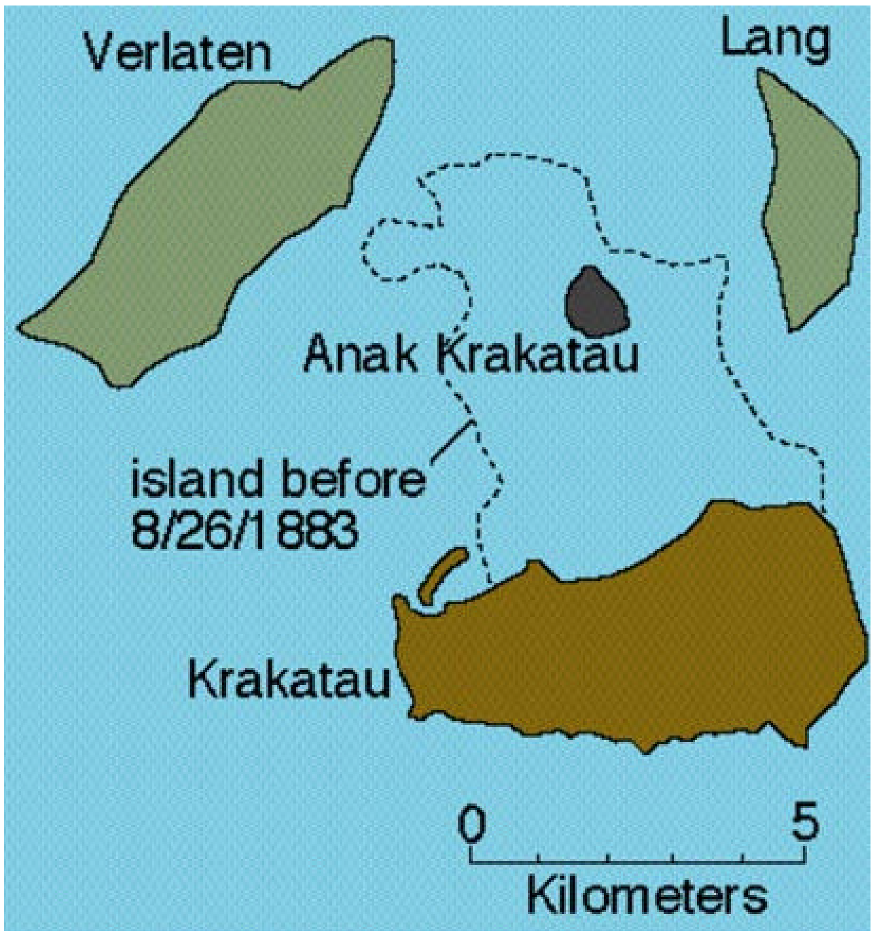


Figure 3. Map showing the remnant of Rakata Island (now called Krakatau Island) after the 1983 explosion and collapse and the new volcano of Anak Krakatau that subsequently emerged from Krakatau's sunken caldera (Modified after Simkin and Fiske, 1983)

The submarine eruptions of Krakatau continued in the evening and night of the 27 th of August but all activity stopped in the morning of the 28th. However, on October l7, 1883 there was again a small submarine eruption, when mud was ejected and a small wave was generated (Verbeek, 1884).

Tsunami Source Dimensions: The dimensions of the tsunami generating area, as well as the volume of water displaced by the mass waste of the volcanic structure edifice due to the 1883 explosions and collapses of Krakatau, can be estimated from post disaster data collection and the bathymetry of the sea floor.

Prior to Krakatau's paroxysmal phase, the island of Rakata had an average elevation of about 212 m (700 feet). However, following the fourth major explosion, 40 sq. Km of the island were reduced to an extensive depression with the depth of more than 275 m (900 feet) below sea level. The huge underwater caldera that was formed by the massive collapse was about 7 km in diameter. The three remaining islands of Verlaten, Lang and Krakatau – the latter being the remnant of Rakata, surround the caldera after the final collapse. The total horizontal extent of the area affected by the collapse and other kinematic processes which contributed to tsunami generation, is estimated at about 40 sq. Kms.

Although the bathymetry of Krakatau's underwater caldera changed considerably after the birth of the Anak Krakatau volcano, review of original and subsequent bathymetry shows a complex relief of the sea floor between the three remaining islands. Following the 1883 events, the water depth between the islands of Lang and Verlaten was about 70 m. However, within this area there were two small basins with depths of about 120 m. The depth of the main caldera depression was about 270 m. The relief within this caldera depression appeared to have an eccentric uplift on one side which was about 60 m higher that the bottom of the basin. Further examination of the bathymetry showed that a central ridge of about 25m in height separated the two deeper basins on the sea floor. The existence of this ridge indicates that two events of major explosion/collapse took place, rather that a single one. The significance of two separate explosion/collapse events is that there were two discreet tsunamigenic sources and that two major tsunamis were generated on August 27, 1883 – although there is no data to support how far apart in time these tsunamis were generated. Perhaps the second depression of the underwater caldera was caused by a collapse that followed the fifth explosion at 10:52, but this cannot be concluded with certainty.

Finally, the total volume of seawater displaced by the massive kinematic processes described above, is estimated to have been at least 20 cubic Kilometers. Therefore, given these approximate source dimensions, the tsunami's greatest initial wavelegth is estimated to have been as much as about 7 km – the size of the caldera – and the greatest period of the resulting waves, no more than 4-5 minutes. Unless the two explosions/collapses – described above – occurred at a very close time interval, the wavelengths and periods of the resulting waves from each tsunami event would be expected to have had even shorter wavelengths and periods.

TSUNAMI TRAVEL TIMES

The origin time of the major tsunami has been assumed to be 10:02 (GMT) on August 27 – which was the time of the fourth colossal paroxysmal eruption/explosion/collapse. However this origin time may be somewhat wrong as it took several minutes for the volcano to collapse and for the tsunami to be generated. Furthermore, as the bathymetric data indicates, there were two separate tsunamis generated with origin times that may have been different. Using the 10:02 (GMT) as the major tsunami origin time, it took about 25 minutes for the first wave to reach the nearest land point on Sumatra. It took considerably longer - in some cases as much as an hour - for the waves to reach major cities and villages on the Sunda Strait.

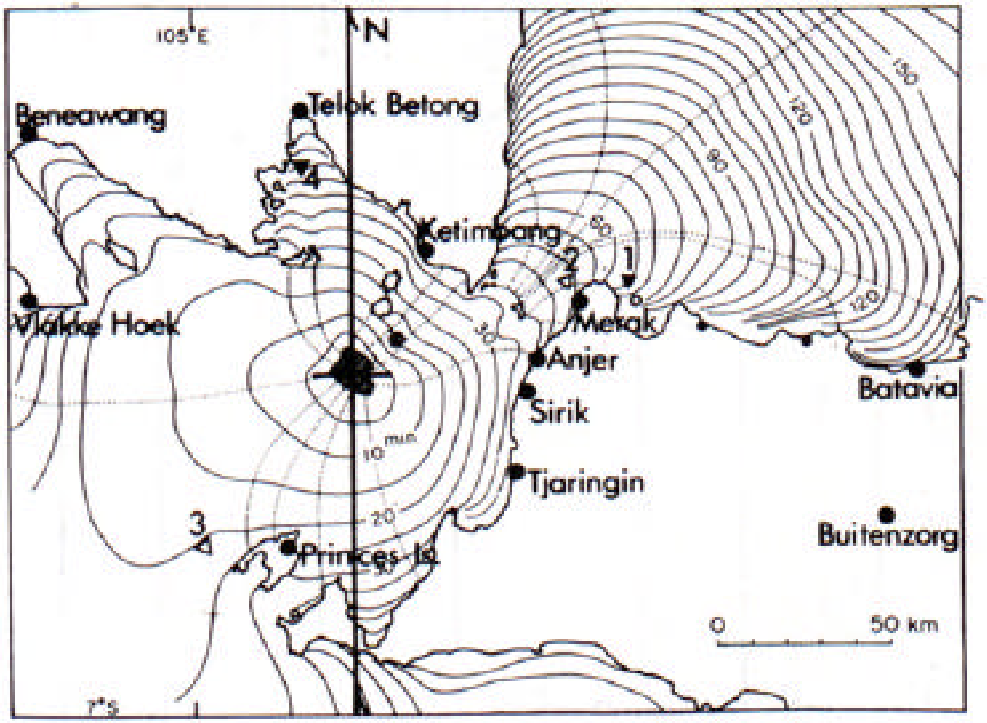


Figure 4. Travel Time of Major Tsunami from Krakatau's Fourth Explosion and Collapse (Modified after Yokohama, 1981)

NEAR FIELD TSUNAMI EFFECTS

The combination of the fourth colossal explosion and subsequent massive flank failures and caldera collapses of Krakatau generated catastrophic tsunami waves. Because of the relative shallow bathymetry of the Sunda Strait, it took almost an hour for the destructive waves to reach the nearest coastal settlements of western Java and southern Sumatra. In certain areas, the waves swept inland for several kilometers, destroying virtually everything in their path. A total of 295 towns and villages were washed away. A total of 36,417 people were drowned. Maximum runup was as high as 37 m. (120 ft.) along certain areas.

The huge tsunami was well documented in terms of visual observations of heights reached along the coasts of Java and Sumatra as well from a recording at a tide gauge at Batavia (Jakarta). Since there is good descriptive documentation of the tsunami effects, the following is only a very brief description of the near field effects of the 1883 tsunami in Java and Sumatra. Many of the names of towns and villages of this region provided here were taken from older accounts. Some of these names have since changed. For example Batavia is now Jakarta.

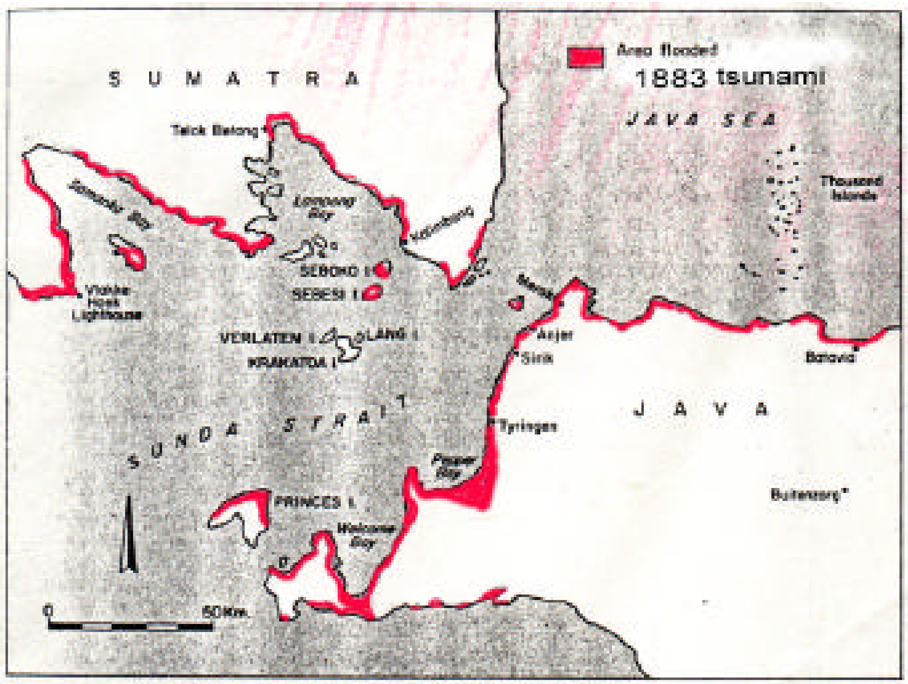


Figure 5.   The extent of maximum inundation from the tsunami(s) generated by the August 27, 1883 explosions and collapse of the volcano of Krakatau (Modified after Symons, 1888)

Island of Sumatra (Telok Batong, Vlakke Hook)

The tsunami travel time to the closest villages of Sumatra was about 1 hour after the explosion of Krakatoa. At Telok Batong, tsunami waves up to 22 meters (72 feet) completely submerged the village. At Vlakke Hook the maximum tsunami wave height was 15 meters.

Island of Java {Sirik, Anjer, Tyringen, Merak, Batavia (Jakarta) and Surabaya}

Destructive tsunami waves reached the Western coast of Java within an hour after the fourth explosion and ensuing collapse of Krakatau. The village of Sirik was almost entirely swept away. It took also about one hour for the destructive waves to reach Anjer where a 10-meter wave completely overwhelmed the lower part of town. At Tyringen, waves ranged from 15 - 20 meters in height (up to 6O ft) while at Merak, the waves reached a maximum of 35 meters.

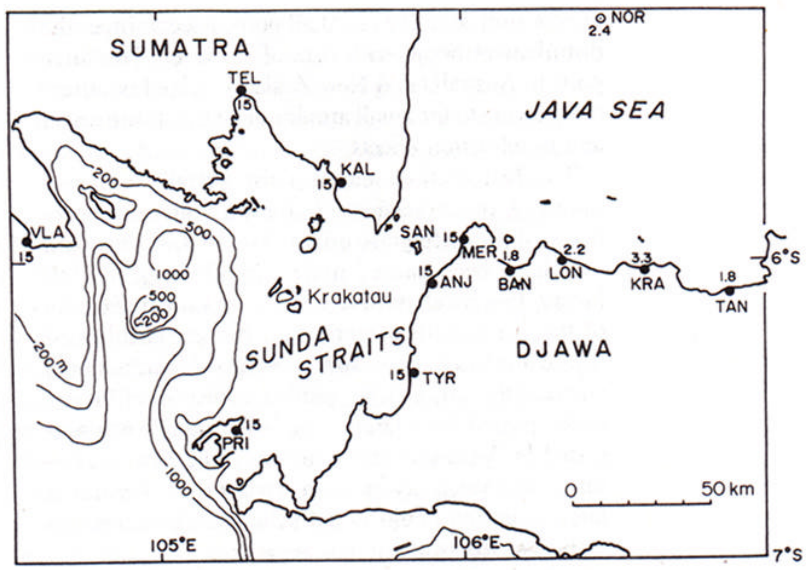


Figure 6. Maximum runup heights (in meters) of the tsunami(s) of August 27, 1883 at coastal towns of Southern Sumatra and Western Java (Modified after Symons, 1888)

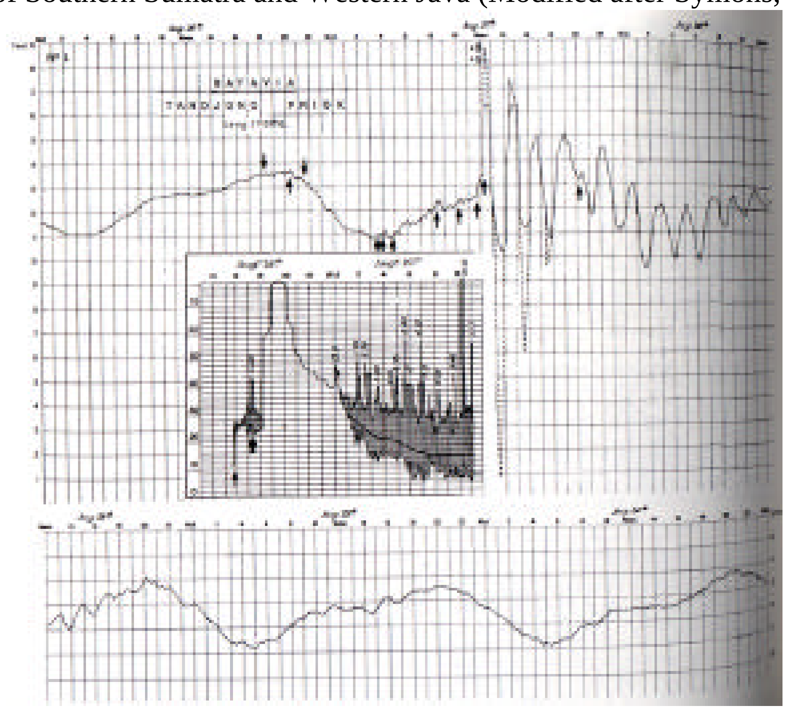


Figure 7. The tsunami(s) from the August 27, 1883 explosions and collapse of the volcano of Krakatau as recorded by the tide gauge at Batavia (Jakarta). Superimposed on the tide gauge record is a barograph record, which shows the early arrival of the atmospheric pressure waves and the sea level oscillations, recorded by the tide gauge prior and after the arrival of the tsunami. (Modified after Verbeek, 1884)

It took approximately 2.5 hours for the tsunami waves to refract around the western end of the island of Java and to reach Batavia (Jakarta). Maximum waves of 2.4 meters were reported there with a very long period of 122 minutes. By the time the tsunami reached Surabaya, at the eastern part of Java, the reported wave height was only 0.2 meters. The tsunami travel time to Surabaya was 11.9 hours.

FAR FIELD TSUNAMI EFFECTS

Because of the short periods and wavelengths, the height of the tsunami waves attenuated considerably with distance away from the source. The far field effects were negligible. However, small sea level oscillations from Krakatau's major explosion and collapse were observed or recorded by tide gauges around the world, as far away as Hawaii, the American West Coast, South America, and even as far away as the English Channel in France and England. Some of the tide gauge records were of the actual tsunami waves, while other recorded or observed sea level disturbances appear to have been caused by the atmospheric shock pressure of the powerful explosions of the volcano.

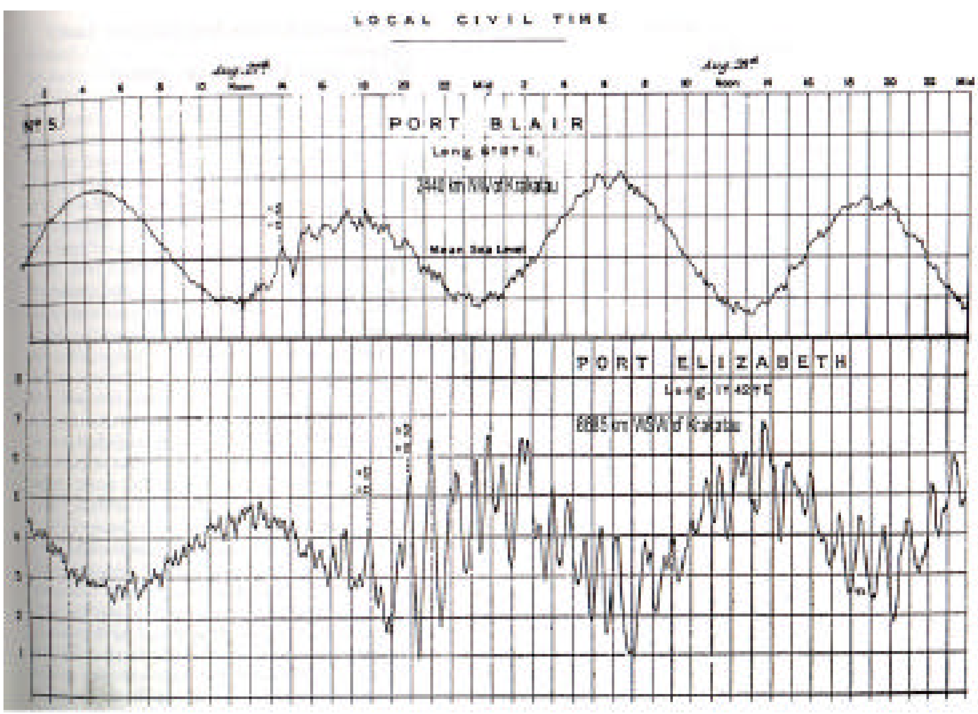


Figure 8. The tsunami(s) from the August 27, 1883 explosions and collapse of the volcano of Krakatau as recorded by tide gauges at Port Blair in the Andaman Islands and at Port Elizabeth, South Africa (Modified after Wharton & Evans, 1888).

Using the time of Krakatau's fourth explosion as the tsunami origin time, it is estimated that it took 12 hours for the tsunami waves to reach Aden on the southern tip of the Arabian Peninsula, some 3800 nautical miles away from the Sunda Strait. Unfortunately there was no operating tide gauge. The wave reported at Aden probably represents the one generated in the Sunda Strait. The travel time of a little over 300 nautical miles per hour to Aden appears reasonable. There were no land boundaries on the Indian Ocean side of the Sunda Strait to prevent the tsunami waves from Krakatau from spreading and traveling in a westward direction. The tide gauges operating at Port Blair in the Andaman Islands and at Port Elizabeth in South Africa recorded these direct tsunami waves.

There were many recordings or observations of small sea level oscillations around the world. The oscillations were detected by tide gauges in South Africa (4,690 miles away), at Cape Horn (7,820 miles away), and Panama (11,470 away). However, some of the observed or recorded disturbances on the coasts of America and Europe, originally attributed to the tsunami from Krakatau, did not have arrival times that corresponded to actual tsunami travel times.

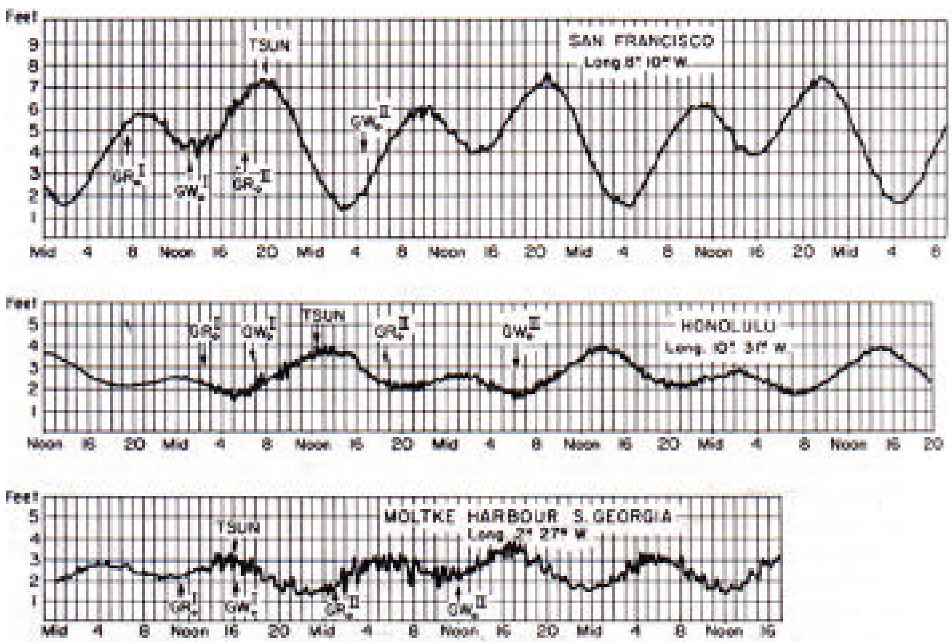


Figure 9. The tsunami(s) from the August 27, 1883 explosions and collapse of the volcano of Krakatau as recorded by tide gauges at San Francisco, Honolulu. and at Moltke Harbor, South Georgia (Modified after Press and Harkrider 1962).

It is doubtful that the sea level oscillations reported or recorded at distant locations in the Pacific or in the Atlantic Ocean represent the actual tsunami generated in the Sunda Strait. Very little, if any at all, of the tsunami energy could have escaped the surrounding inland seas to the east of the Sunda Strait. Most probably, the small waves that were observed or recorded in the Pacific as well as in the Atlantic were generated by the atmospheric pressure waves from the major Krakatau explosion, and not from the actual tsunami generated in the Sunda Strait.

The Honolulu tide gauge in the Hawaiian Islands recorded a small oscillation of 0.24 meters, 17 hours after the explosion of Krakatau. In Alaska's Kodiak Island a small oscillation of 0.1 meter was recorded. In San Francisco, California, a 0.1-meter sea level oscillation was recorded 20 hours after Krakatau's explosion. In Japan, a small sea level oscillation was recorded at Honshu-Sagami and at Shikoku-Satsuma. In Australia, a trace of the tsunami was recorded. It was less than 0.1 meter. In New Zealand a 0.3-meter change in water level was reported.

ATMOSPHERICALLY GENERATED TSUNAMIS

A rapidly moving atmospheric pressure front moving over a shallow sea can couple with the sea surface and generate tsunami-like waves. It has been clearly established that the atmospheric pressure shock waves from the explosions of Krakatau were significant. They circled the earth and were recorded by barographs throughout the world. In fact, some as many as seven times as the wave bounced back and forth between the eruption site and its antipode (located near Bogota, Colombia) for 5 days after the explosion.

Such atmospheric pressure wave coupling from the Krakatau main explosion, traveling around the earth, gave rise to unusual sea level oscillations in bays and estuaries far distantly from the source region. Also, the atmospheric pressure wave appears to have been responsible for sea level oscillations recorded by many tide gauges.

In all probability, the small sea level oscillations that were observed in the Pacific as well as in the Atlantic were generated by the atmospheric pressure waves that resulted from the major Krakatau explosion, and not from the actual tsunami generated in the Sunda Strait. The waves recorded by gauges in Honolulu, San Francisco and elsewhere were caused by the atmospheric pressure waves, because their timing is not consistent with tsunami travel times. For example, if it took 11.9 hours for the actual tsunami to reach Surabaya on the eastern end of Java, how could it take only 17 hours to reach Honolulu and 20 hours to reach San Francisco, particularly since little or no tsunami energy could escape the inland seas to the east of the Sunda Strait? Similarly, the unusual sea level disturbances observed in such distant locations as the Bay of Cardiff can only be explained by coupling of the sea surface with the atmospheric pressure wave from the major explosion of Krakatau.

Since the shock wave travel at the speed of sound (approx. 340 meters/sec - about 1225 Km/hour) the travel time of the atmospheric pressure wave to Cardiff could be estimated. At that speed, and the shorter distance in a westward rather than eastward direction, an 18-hour travel time of the atmospheric wave from Krakatau's fourth paroxysmal explosion to Cardiff seems possible. There is no way that a direct wave could travel on the surface of the ocean to reach Cardiff in such a short time – particularly considering that it took 12 hours for the actual waves to just reach Aden on the Arabian Peninsula. Additionally, it appears the configuration and geometry of the Bay at Cardiff, the offshore bathymetry, and the direction of approach of the shock wave were optimum for atmospheric coupling that caused the observed sea level disturbances. Additional studies of microbarograph recordings of the atmospheric wave caused by the Krakatau explosions would be very helpful to further confirm the atmospheric origin of the sea level disturbances that were observed or recorded.

SUMMARY AND CONCLUSIONS

Geologic evidence and observations reported in the scientific literature indicate that several tsunamis were generated in the Sunda Strait during the paroxysmal phases of Krakatau's volcanic activity on August 26-27, 1883. During a ten hour period, Rakata Island was significantly altered by several subsidences, explosions and large waves following four Plinian and several submarine Surtsean (phreatomagmatic) eruptions and explosions.

A sub aerial collapse of Krakatau's caldera begun in the northern part of Rakata in the vicinity of the Perboewatan crater. Subsequent tsunami waves - generated by flank collapse activity - triggered extensive landslides of previously deposited pumice on Verlaten and Lang islands and generated additional large local tsunami-like waves. One – but more likely two - major explosions followed by extensive flank failures and massive caldera collapses of Krakatau - on what used to be Rakata Island - generated the more destructive of the tsunamis observed in the Sunda Strait. The existence of a ridge separating the resulting submarine caldera depression is indicative of two distinct large explosion/collapse events. The composition of deposits on neighbor islands also supports such mechanism of tsunami generation during Krakatau's paroxysmal phase.

The largest of the destructive tsunami waves were generated a little after 10:02 on August 27th (GMT), from the combination of explosion, subsidences, caldera collapses, landslides and massive underwater flank failures. Another substantial tsunami was generated at 16:38 by an additional phase of Krakatau's caldera collapse.

The small waves and other sea level disturbances that were observed at great distances were generated by atmospheric, air-to-sea coupling of shock waves from the major Krakatoa explosion, and not from the actual tsunami generated in the Sunda Strait.

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