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QuickBird Image of Kalutara, Sri Lanka (after tsunami)

The above image was acquired by QuickBird satellite on December 26, 2004 at about 11:20 am local time, shortly after the first series of tsunami waves struck the shoreline.

The Earth From Afar: Image Review

Editor: Paul R. Baumann
Department of Geography
State University of New York at Oneonta
Milne Library 317
Oneonta, NY 13820
U.S.A.

Remote Sensing Images of a Tragic Natural Disaster: The 2004 Indian Ocean Tsunami

Paul R. Baumann
Department of Geography
State University of New York
Oneonta, NY 13820
U.S.A.

M. Duane Nellis
Office of the Provost
Kansas State University
Manhattan, KS 66506
U.S.A.

The World recently experienced a major natural disaster when a large tsunami hit extensive coastal areas around the Indian Ocean on December 26, 2004, tragically killing thousands of people and reshaping many coastal environments. Although not the largest natural disaster ever encountered by the World (Table 1), this tsunami did generate, among other things, a tremendous amount of interest and concern by people who live in coastal areas and throughout the world. Through the use of maps and satellite images this paper examines the nature of tsunamis, and more specifically, looks at the December 26 tsunami and its impact on the community of Lhoknga, Indonesia as an example of the devastation and carnage a tsunami can create.

Tsunami

The word, *tsunami* is Japanese in origin and means "harbor wave." Some Japanese fishermen first formulated the term when they returned home to discover their harbor and surrounding area destroyed by a large wave even though they had not experienced any such wave on the open sea. *Tsu* means "harbor" and *nami* means "wave." Sometimes tsunamis are referred to as "tidal waves" or "seismic sea waves." Tsunamis are not "tidal" in function or strictly "seismic" in origin. Tides are caused by gravitational influences from the moon, sun, and planets. "Seismic" indicates an earthquake condition, but a non-seismic event, such as a landslide, submarine volcanic eruption or meteorite impact, can also cause a tsunami. However, undersea earthquakes are the most common cause for tsunamis. A small earthquake might also generate an undersea landslide capable of producing a tsunami.

Table 1 Significant Earthquakes

Date	Location	Fatalities
May 20, 526	Antiochia, Syria	250,000
1138	Ganzah, Aleppo, Syria	230,000
1201	Upper Egypt or Syria	1,100,000
January 23, 1556	Shaanxi, China	830,000
October 11, 1737	Calcutta, India	300,000
February 28, 1780	Iran	200,000
December 16, 1920	Ningxia-Kansu, China	200,000
September 1, 1923	Kanto, Japan	143,000
May 22, 1927	Tsinghai, China	200,000
July 27, 1976	Tangshan, China	255,000*

Source: http://en.wikipedia.org/wiki/List_of_earthquakes
*Fatalities estimated as high as 655,000.

A tsunami generally occurs when a section of the sea floor suddenly changes and vertically displaces the overlying seawater. Such changes in the sea floor are most common along the edges of tectonic plates where earthquakes frequently happen. However, most undersea earthquakes do not produce tsunamis, only those that create a major abrupt shift in the sea floor. Such earthquakes occur when denser oceanic plates move under continental plates in a process known as *subduction*. Subduction earthquakes are especially effective in creating tsunamis.

A tsunami can develop when a disturbance displaces a large water mass from its equilibrium position. In the case of earthquake-produced tsunamis, the seawater's equilibrium is disrupted with the sudden uplift or subsidence of the sea floor. Sometimes, near the origin of the uplift or subsidence, the overhead water surges upward creating a high ridge or drops down forming a deep trough. Anything on the sea surface at this point will be pushed up to ride the ridge or pulled down into the trough. Generally ships do not survive either of these conditions.

As the tsunami starts moving across the open sea, it acts like broad swells on the water surface, and boats and ships are not likely to experience much difference in the normal wave movement. However, water might be moving at speeds of up to several hundred kilometers per hour. As a tsunami moves into shallower waters near a coastline, its speed diminishes and its height increases. In the open sea its wave speed and wave height remain fairly constant but as it travels into shallower water, bottom friction and turbulence start to slow it down. Even though a tsunami's speed might slow down in shallow water, it continues to possess a tremendous amount of energy. It has the potential of stripping beaches of sand and vegetation, crushing homes and other structures, and surging hundreds of meters inland. At the same time, as the waves approach the shore, their heights are forced up over the normal sea level. As they move onshore tsunami waves may reach a maximum vertical height above sea level, often called a runup height, of 10, 20, and even 30 meters. At 30 meters (98.4 ft) a tsunami wave is equivalent in height to a nine to ten story building.

December 2004 Earthquake and Tsunami

On December 26, 2004 at 07:58:53 AM (local time) a shallow, thrust-type earthquake occurred off the west coast of northern Sumatra. It was initially reported as 6.8 on the Richter scale. Using the moment magnitude scale, which is a successor to the Richter scale and more accurate on large quakes, U.S. Geological Survey first reported a magnitude of 8.1. Later as more data became available, it revised the quake's magnitude to 8.5, 8.9, and finally to 9.0.

In the last one hundred years only four other megathrust earthquakes (9.0 magnitude or higher) have been recorded (Table 2). Each of these earthquakes was located around the edge of the Pacific Ocean, which makes this new quake unique since it occurred in the Indian Ocean. The only other large recorded earthquakes not located in the Pacific Ocean were in Assam (India) - Tibet (China) and the Banda Sea, Indonesia. Also, each of these megathrust earthquakes generated a tsunami but the death levels were considerably lower since the affected areas had low population densities. It needs to be noted that the high death toll associated with the recent disaster relates more to the tsunami than the earthquake, even though the tsunami was a direct product of the earthquake. There have been some very high death tolls (Table 1) related directly to other earthquakes.

This megathrust earthquake occurred at the interface of the India plate and the Burma microplate. The release of stress build-up resulted in the India plate subducting below the overriding Burma microplate. The Burma microplate experiences considerable strain due to the oblique convergence of the India and Australia plates on its west side and pressure from the Sunda and Eurasian plates on its east side (Figure 1). The India plate is moving against the Burma

Table 2 Large Earthquakes

Location	Date UTC	Magnitude	Latitude-Longitude
1. Chile	1960 05 22	9.5	38.24 S, 73.05 W
2. Prince William Sound, Alaska	1964 03 28	9.2	61.02 N, 147.65 W
3. Andreanof Islands, Alaska	1957 03 09	9.1	51.56 N, 175.39 W
4. Kamchatka	1952 11 04	9.0	52.76 N, 160.06 E
5. Off the West Coast of Sumatra	2004 12 26	9.0	3.30 N, 95.78 E
6. Off the Coast of Ecuador	1906 01 31	8.8	1.0 N, 81.5 W
7. Rat Islands, Alaska	1965 02 04	8.7	51.21 N, 178.50 E
8. Assam - Tibet	1950 08 15	8.6	28.5 N, 96.5E
9. Kamchatka	1923 02 03	8.5	54.0 N, 161. 0 E
10. Banda Sea, Indonesia	1938 02 01	8.5	5.05 S, 131.62 E
11. Kuril Islands	1963 10 13	8.5	44.9 N, 149.6 E

Source: http://neic.usgs.gov/neis/eq_depot/world/1952_11_04.html microplate in a northeastward direction. This movement has been recorded at about 6 cm per year (2.4 inches/year). The front edge of the India plate encounters increasing temperatures and pressures as it slips deep beneath the Burma microplate. Eventually the edge becomes magma that might escape through volcanic eruptions and/or flows. If plates lock for a long period of time and disrupt this process of magma flow, the build up of stress can result in a massive earthquake and tsunami. No significant quake had occurred between these plates since 1833, hence the huge force of this one. The Indian plate slid approximately 35m (115 ft) beneath the Burma microplate. The slide of the India plate released the Burma microplate from its tension, causing it to spring suddenly upward by about 6m (20 ft) and generate the massive tsunami. This upward bulge might have altered the topography, as well as the geographic positions, of the Andaman and Nicobar islands.

Based on the locations of the aftershocks an estimated 1200 km (750 miles) of fault line shifted 15 m (50 ft). This shift occurred as the India plate moved under the Burma microplate. This movement took place in two phases over several minutes. The first phase resulted in a rupture that was approximately 400 km (249 miles) long by 100 km (62 miles) wide and at a depth of 30 km (18.5 miles) below the sea floor. The speed of this rupture was about 2 km (1.25 miles) per second, starting off the west coast of the Indonesian territory of Aceh. It moved northwest for 100 seconds and then paused for about another 100 seconds. After the pause, the rupture moved again northward toward the Andaman and Nicobar Islands. An estimated 116 aftershocks between 4.0 and 7.1 magnitude occurred along this rupture between December 26 and January 2 (Figure 1).

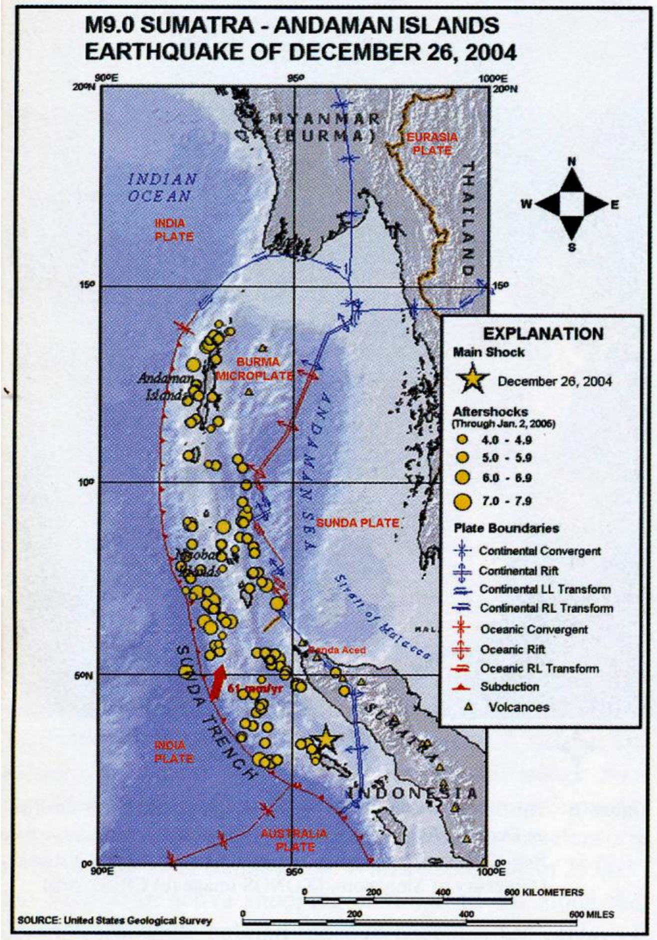

Figure 1 Aftershock Map as of January 2, 2005 - Modified from:http://earthquake.usgs.gov/eqinthenews/2004/usslav/

The Institute of Computational Mathematics and Mathematical Geophysics in Novosibirsk, Russia created a map that shows in 30-minute intervals the amount and area of the Indian Ocean covered by the tsunami (Figure 2). The red area estimates the rupture that produced the tsunami. The east-west waves were larger than the north-south waves and created significantly more damage. These waves approached speeds of 900 kilometers per hour (550 miles per hour). The west coast of Sumatra received the first waves approximately 20 minutes after the earthquake. As the waves came ashore, they were 10m to 15m (30ft to 50ft) in height. No accurate count exists on the number of waves but reports indicate from five to six waves. Lhoknga and its neighboring communities on the west side of Sumatra basically had no warning time.

Physical Setting

Indonesia consists of four large islands, formerly referred to as the great Sunda complex, and a large number of smaller islands. The four large islands are Sumatra, Java, Borneo, and Sulawesi. Sumatra encountered the greatest amount of devastation from the tsunami, especially at the north end and

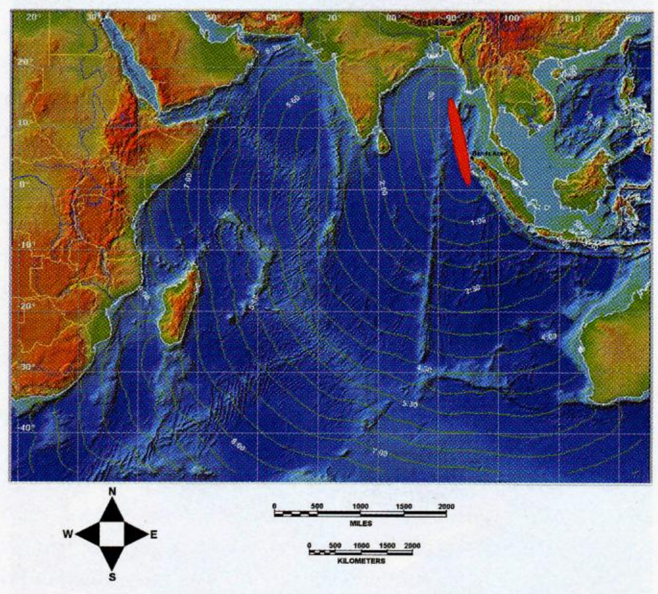

Figure 2 Map shows in 30-minute intervals water surface covered by the December 26 Tsunami. Map prepared by Dr. Viacheslav Gusiakov, Institute of Computational Mathematics and Mathematical Geophysics, Novosibirsk, Russia.

on the west side of the island. Administratively, Sumatra is subdivided into provinces, except for one area that has been elevated to the level of being a special territory. This area is the Special Territory of Aceh (Figure 3) and it was this area that experienced the greatest number of deaths and destruction. Of the total number of deaths due to the tsunami, a number that continues to grow, between 65 and 70 percent occurred in Aceh.

The Barisan Mountains delineate Sumatra. They extend the length of the island. The coastal lands on the east side of the island are, in general, swampy and poorly drained. The one major exception is on the northeast coast where the land is well drained and has fertile alluvial soils, ideal for agriculture. These productive agricultural lands extend along the eastside of Aceh, up to its northern tip where the territorial capital city of Banda Aceh is located. Most of Aceh's development and population occurs in this area.

In Aceh, the Barisan Mountains rise abruptly from the lowlands and provide little productive land. They also form a major communication and transportation barrier between the west and east sides of Aceh. In general, the west coast of Sumatra lacks flat land for any major development. However, in Aceh, a few large pockets of coastal land exist that are suited for agriculture. The town of Lhoknga occupies one of these pockets. Not as many people reside on the west side of

Figure 3 Map of The Special Territory of Aceh

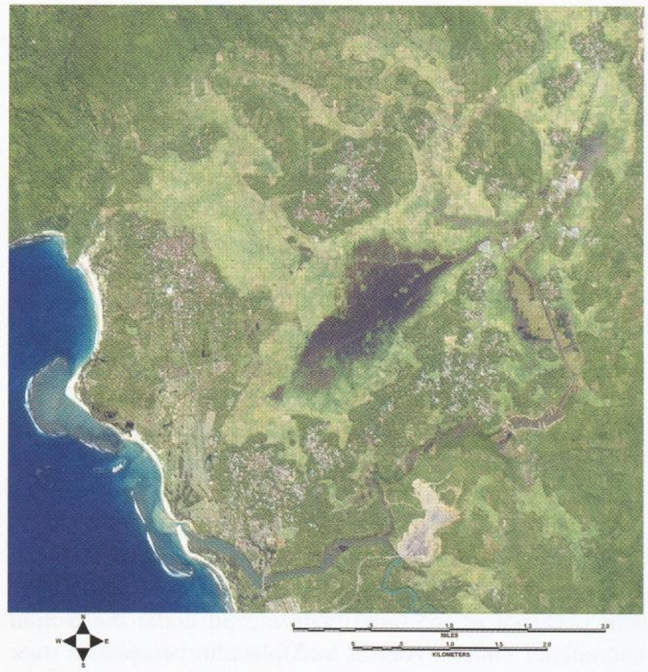

Figure 4 This image was taken by Space Imaging's IKONOS satellite on Jan. 10, 2003. Image acquired and processed by Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore, IKONOS image (c) CRISP 2004

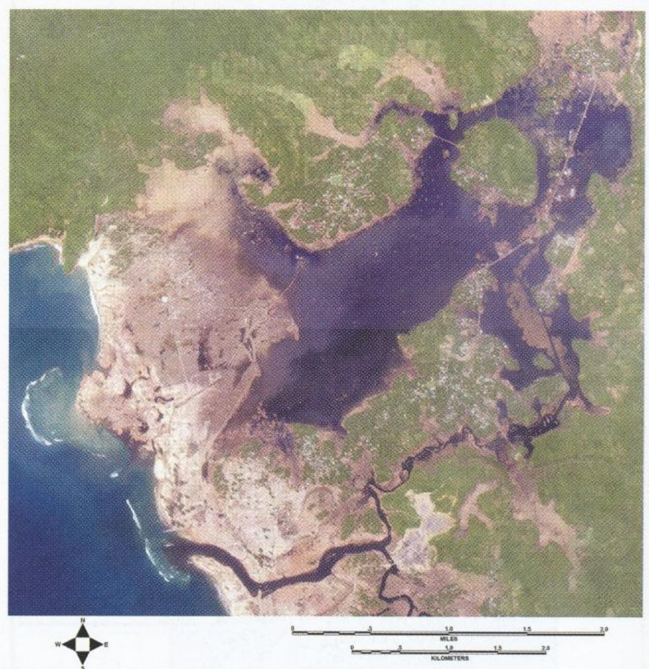

Figure 5 This image was taken by Space Imaging's IKONOS satellite on Dec. 29, 2004. Image acquired and processed by Centre for Remote Imaging, Sensing and Processing (CRISP), National University of Singapore, IKONOS image (c) CRISP 2004

Figure 6 The mosque located in the center of Lhoknga. Photo provided by the U.S. Department of Defense.

Figure 7 The Raba Lhoknga River valley from the coastline. Photo provided by the U.S. Department of Defense.

Aceh in comparison to the east side. However, the people who do reside here mainly live along the coast and were the first to experience the power and intensity of the December 26 tsunami.

Lhoknga Region

Figures 4 and 5 were taken by Space Imaging's IKONOS satellite on January 10, 2003, and December 29, 2004, respectively. The resolution for these images is 2 meters. The first image was recorded about one year before the earthquake/tsunami occurred and the second image was captured three days after the devastating tsunami hit Sumatra. Figure 4 shows Lhoknga [Lhonga], a town 17 kilometers (10 miles) southwest of Banda Aceh. With a population of 25,000, the town is an active shopping area spread out along the coastline. A white-colored mosque occupies the center of the town indicating that it is also a religious center. The beautiful white Lhoknga and Lumpuk beaches line the coast.

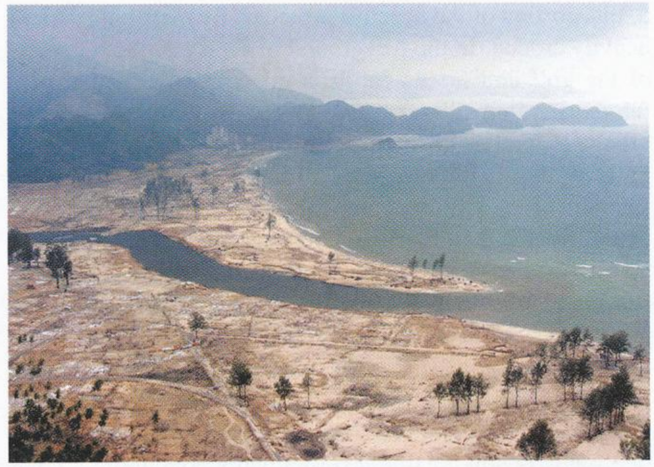

Figure 8 The Raba Lhoknga River and coastline south of Lhoknga. Photo provided by the U.S. Department of Defense.

The white sand and clear waters are perfect for fishing, boating, snorkeling and bathing. Coral reefs exist a short distance from most of the beach line, making surfing possible. To the south, just outside Lhoknga, two Indonesian army bases face each other across the Raba Lhoknga River in the village of Mon Ikeun. A golf course is located next to the base on the north side of the river and near the beaches.

Behind Lhoknga several other densely settled communities exist, mainly on what appears to be slightly elevated, tree covered knolls. In between the knolls, the land is flat and covered by small rice fields. Some flooded fields occupy the center of this farming area apparently with overflow water from adjacent irrigation canals. Fish farms can be detected along the Raba Lhoknga River that meanders along the bottom portion of the image.

The tsunami destroyed most of this landscape as illustrated in Figure 5. The destruction extended 6 km (3.7 miles) inland, to the end of the newly formed lake. Except for the mosque, Lhoknga, as a city, no longer survives. Figure 6 was taken from a U.S. military rescue helicopter. It shows the mosque surrounded by almost complete destruction. At this point, the waves most likely exceeded 15 meters (50 feet) when they struck the shore. Nearly ninety percent of all structures are gone and the few remaining structures are probably heavily damaged. The land is denuded and most likely covered with debris and salt. Three-fourths of Lhoknga's population perished.

Starting at the coastline Figure 7 is looking down the Raba Lhoknga River valley. Very few trees and other vegetation remain near the coast. Coconut palms and pine trees lay uprooted on both banks. The bridge that crosses the river is gone. From first-hand accounts the steel girders from the bridge had snapped in two and sit half-submerged upriver, tangled in trees and chunks of concrete. A sole reinforced concrete support stands in the middle of the river. The bridge's shoulder on the south side of the river can be seen in Figure 7. Figure 8 shows the denuded coastline and the mouth of the Raba Lhoknga River. As seen in Figures 4 and

5, this portion of the beach is protected by reefs but it is still heavily eroded. In the foreground of Figure 8, the remnants of the golf course can be detected. Trees line what were fairways. Immediately next to the golf course was the village of Mon Ikeun. Of the estimated 1,000 people residing in this village, no more than 200 survived. All that remains standing of the military compound located on the north side of the river is a solitary concrete gatepost. This base had housed 300 soldiers and their families but only six people survived. Some of the events described in this section of the paper came from three young men who walked 95 miles along the coastline, trying to return home to Banda Aceh. They encountered devastation the entire distance.

Farther inland from Lhoknga, the area covered by small rice fields is now a large lake, probably containing a large amount of salts and contaminates. The lake is approximately 5.5 km (3.4 miles) in length by 1.1 km (.75 miles) in width. One small settlement, that appears to have withstood the tsunami, finds itself on an island within the large lake. Steep-sided, tree-covered hills exist on both sides of the Lhoknga valley; thus, when the tsunami came ashore, its force was funneled down through the highly settled lowland between the hills. The tsunami stripped some hillsides of their trees up to 15 meters above the adjacent lowlands.

Final Remarks

The World was recently reminded of the power of our Earth's natural systems to create huge magnitude events that have major tragic consequences. Through this transfer of massive amounts of energy linked to a substantial earthquake and subsequent tsunami, extensive coastal areas around the Indian Ocean were devastated. Although tsunamis have occurred historically on a regular basis, the circumstances surrounding the displacement of the India plate and the Burma microplate, with the resulting tsunami diffusion pathway, created dramatic and tragic impact on coastal settlements, human life, and environmental systems throughout the Indian Ocean region that will not be forgotten by the World for many years to come and point out the vulnerability of coastal regions to numerous types of environmental hazards. Various types of remote sensing images and photographs can provide a synoptic and timely perspective of the before and after impacts that help document the magnitude of impact of such catastrophes.

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