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Damage to Coastal Villages due to the 1992 Flores Island Earthquake Tsunami

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Abstract—A field survey of the 1992 Flores Island earthquake tsunami was conducted during December 29, 1992 to January 5, 1993 along the north coast of the eastern part of Flores Island. We visited over 40 villages, measured tsunami heights, and interviewed the inhabitants. It was clarified that the first wave attacked the coast within five minutes at most of the surveyed villages. The crust was uplifted west of the Cape of Batumanuk, and subsided east of it. In the residential area of Wuring, which is located on a sand spit with ground height of 2 meters, most wooden houses built on stilts collapsed and 87 people were killed even though the tsunami height reached only 3.2 meters. In the two villages on Babi Island, the tsunami swept away all wooden houses and killed 263 of 1,093 inhabitants. Tsunami height at Riang-Kroko village on the northeastern end of Flores Island reached 26.2 meters and 137 of the 406 inhabitants were killed by the tsumani. Evidence of landslides was detected at a few points on the coast of Hading Bay, and the huge tsunami was probably formed by earthquake-induced landslides. The relationship between tsunami height and mortality was checked for seven villages. The efficiencies of trees arranged in front of coastal villages, and coral reefs in dissipating the tsunami energy are discussed.

Key words: Coastal damage due to tsunamis, coeismic crustal motion, aftershock area, secondary tsunamis by induced landslides, short arrival time of tsunami, liquefaction, sand blow, relationship between tsunami height and ratio of mortality.

1. *Introduction*

A large earthquake with magnitude M_w 7.8 occurred on the north coastal area of the eastern part of Flores Island, Indonesia, at 5 h 29 m GMT (13 h 29 min Flores local time) on December 12, 1992. Most buildings were damaged in Maumere City and its vicinity, where seismic intensity was estimated at 9 to 10 on the Modified

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Mercalli scale or at 6 on the JMA intensity scale. In the city area, evidence of liquefaction, sand blows, and cracks was observed at many places. Additionally, landslides occurred in the mountainous regions.

Several minutes after the main shock, a tsunami attacked the villages on the north coast of the eastern part of Flores Island. The residential area of Wuring village, which is located about 2 km northwest of Maumere on a small sand spit 700 meters long, was hit by the tsunami resulting in the collapse of 80 percent of the wooden houses and the death of 87 persons of the 1,400 inhabitants. The height of the tsunami was only 2.5–3.2 m above mean sea level.

Babi Island, with a diameter of 2.5 km, is located offshore some 40 kilometers northeast of Maumere City. Two villages are situated on the south coast of the island; Muslim in the western part and Christian in the eastern, totalling a population of 1,093. About 3 minutes after the main shock, the first wave attacked both villages, and all houses were washed away; leaving no trace of buildings. The tsunami took the lives of 263 persons.

On the coast near Cape Bunga, the most northeastern point of Flores Island, an extraordinarily large wave attacked the coastal villages. Sea water ran up along a slope and reached a height of 26.2 m above sea level at Riang-Kroko village. Houses were entirely swept away, and nothing remained to provide evidence of human lives there. In this village 137 persons perished due to the tsunami.

We conducted a survey along the coast of the eastern part of Flores Island from December 29, 1992 to January 6, 1993 and visited about 40 coastal villages including Wuring, Babi Island, and Riang-Kroko. We also visited the refugees' tents at Nangahale village, about 30 kilometers east of Meumere, where the survivors from Babi Island stayed temporarily. We measured the tsunami inundation height by detecting traces of sea-water submergence and by questioning eyewitness accounts. We also researched building damage in each village. Additionally, we copied the Indonesian newspaper, "Kompas", dated from December 13 to 30, 1992, from which we could obtain statistical information of human and building damage with the total number of houses and inhabitants of several villages.

In the present study, the characteristics of the earthquake and tsunami are mentioned briefly. Tsunami heights and inundation at coastal villages are described in detail with the statistics of human casualties and building damage. Furthermore, we compare this damage with tsunamis in Japan.

2. *Historical Background of Tsunamis in Indonesia*

2.1 Distribution of Earthquakes and Tsunamis in the Central and Eastern Parts of Indonesia

Virtually all Indonesian territory consists of island arcs, accompanied by parallel ocean trenches. Naturally, the seismicity of most of the territory is generally active.

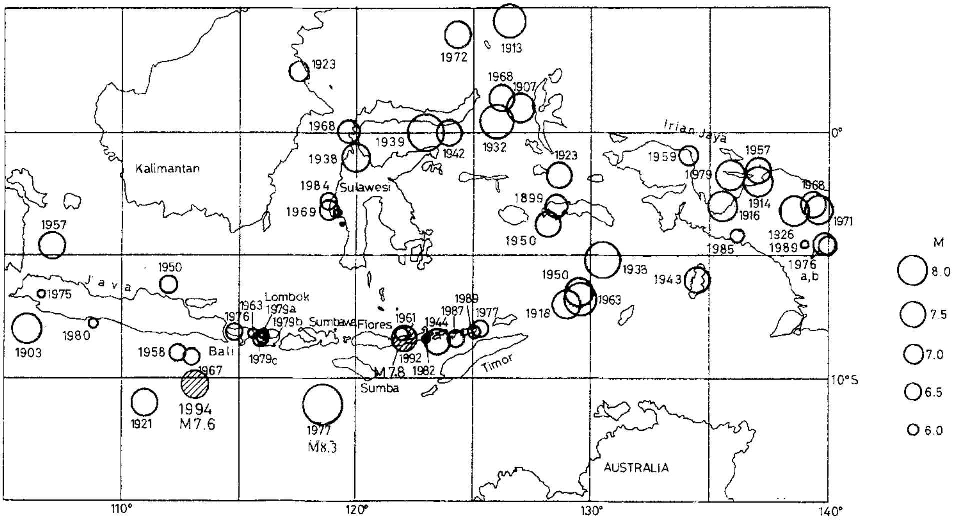

Figure 1
Distribution of the epicenters of earthquakes with damage, which occurred in the central and eastern parts of Indonesia since the beginning of this century. Shadings represent the 1992 Flores and the 1994 East Java earthquakes.

A tsunami catalog of the western Pacific was published by SOLOVIEV and GO (1974), and they also published an additional catalog for the entire Pacific coast (SOLOVIEV and GO, 1987). In addition, SUNARJO and TAJAN (1993) created a table of tsunamis in Indonesia. UTSU (1991) edited a catalog of all destructive earthquakes in the world, in which tsunamigenic earthquakes in Indonesia are listed. A short article in the newspaper KOMPAS, dated December 14, 1992, introduced destructive earthquakes and tsunamis in the region of Flores-Alor Archipelago and its vicinity. On the basis of those materials, we made the map of the distribution of damaging earthquakes in the central and eastern parts of Indonesia (Fig. 1). Figure 1 shows the locations of the epicenters.

A group of earthquakes occurred since 1964 in the Flores-Alor region, and seismic activity has increased since 1977. In 1977, a massive earthquake of normal fault type with magnitude 8.3 occurred in the sea south of Sumba Island, and 189 deaths were attributed mainly to the tsunami (KATO *et al.*, 1993). Another group of earthquakes struck the region of Bali and Lombok Islands, where seismic activity has increased since 1963. Earthquakes causing damage occur rarely in the region from Sumbawa Island to the western part of Flores Island, and a seismic gap seems to form in the area between the two seismically active areas.

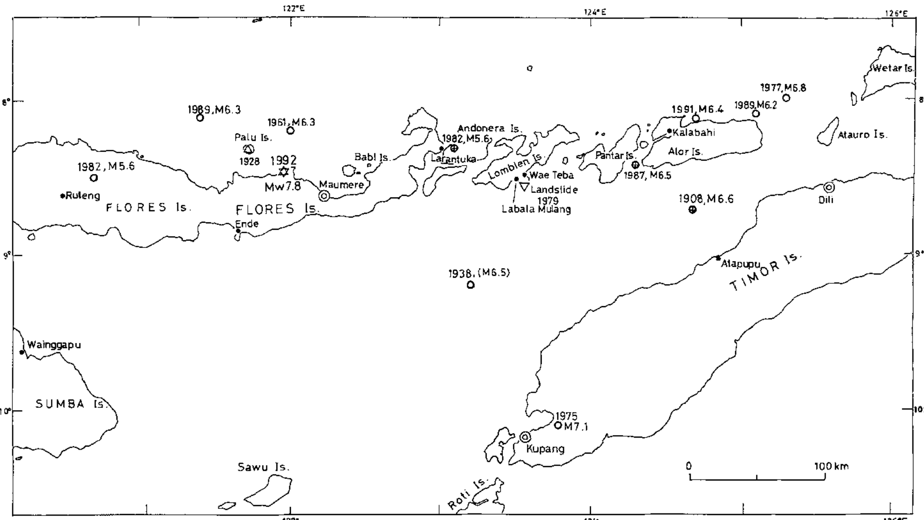

Figure 2
Distribution of earthquakes and tsunamis with damage, which occurred in the Flores-Alor region since the beginning of this century. Open circles show earthquakes with damage, circles with crosses show earthquakes with tsunamis. A triangle shows a tsunami caused by a volcanic eruption. An inverted down triangle shows a tsunami caused by a landslide.

2.2 Distribution of Earthquakes and Tsunamis in the Region of the Flores-Alor Island Arc

Figure 2 shows the distribution of earthquakes and tsunamis in the Flores-Alor region during this century. The volcanic Island of Palu erupted August 4 to 5, 1928, and a tsunami was induced. Both the eruption and tsunami killed 226 persons in total, 128 of which were victims of the tsunami. On July 18, 1979, a large-scale landslide occurred on the southeast coast of Lomblen Island and generated a large tsunami. The tsunami hit two neighboring villages, Wae-Teba and Labala-Mulang; 539 people were killed and about 700 were missing due to the tsunami (MIYOSHI, 1993). This tsunami was not associated with any earthquake and there were no irregular meteorological conditions on that day. The crust beneath the islands of the Flores-Alor region is basically formed of multiple thick basalt layers, and there are many steep cliffs on the coast in this region. This suggests that landslides can be easily induced by earthquakes or heavy rainfall. In this region, damaging earthquakes have had a tendency to occur more frequently since 1977, the time of the Sumbawa tsunamigenic earthquake of August 19, 1977 with magnitude M_w 8.3.

2.3 Earthquakes and Tsunamis in the Past Ten Years in the Region of Flores Island and its Vicinity

In 1982, two damaging earthquakes occurred on Flores Island. One occurred on August 6, near Retung, an inland city in the central part of the island. The magnitude of the earthquake was 5.6, causing slight building damage. The other occurred in the city of Larantuka, on the easternmost coast of the island. The magnitude of the earthquake was 5.6, and it caused damage in the area extending from the eastern part of Flores Island to the Adonara and Solor Islands. Submarine landslides were induced in the channel between the islands of Flores and Adonara and a small tsunami was generated. Thirteen people were killed, 17 people were seriously injured, 400 people were slightly injured, and 1,875 houses totally collapsed due to the event.

On July 15, 1989, an earthquake with magnitude 6.2 struck the northeastern tip of Alor Island; 7 people were killed and 95 houses caved in. Sixteen days after the previous event, on July 31, 1989, another sizeable earthquake with magnitude 6.3 occurred offshore north of the central part of Flores Island, and a few persons were killed in Maumere City. The damaged area of this event overlapped that of the 1992 Flores Earthquake. Seismic intensity at Maumere was 5 on the MM scale.

One year before the present event, July 4, 1991, an earthquake with magnitude 6.2 (M_s 6.4) occurred along the north coast of Alor Island, near Kalabahi City; 23 persons perished, 181 persons were injured, and 1,150 houses were destroyed. The records of broadband seismographs show that two events occurred sequentially, separated by 2.5 seconds.

2.4 Characteristics of Historical Earthquakes and Tsunamis in the Region of Flores Island and its Vicinity

We can judge that the present event took place in the zone of increased seismic activity in the Flores-Alor region since 1977 (Fig. 3). In particular, we note that

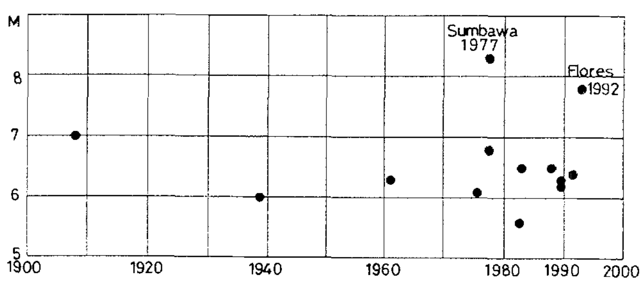

Figure 3
Chronological diagram of earthquakes with damage in the Flores-Alor region.

three earthquakes with magnitudes over 6.0 occurred in the Flores-Alor region within the three years prior to the 1992 Flores earthquake and may be considered as precursors of that event. We also notice that landslides can be easily induced by earthquakes in this district, due to the many steep cliffs of basalt layers and to poor vegetation conditions on the slopes caused by negligible precipitation on land. We should also note that tsunamis were often caused by landslides, which may have been induced both by some seismic or meteorological conditions.

3. The 1992 Flores Earthquake

3.1 Tsunami Source Area

The epicenter was located on the north coastal region of the eastern part of Flores Island, near the Cape of Batumanuk, 35 kilometers northwest of Maumere City. The CMT solution by Harvard University demonstrates that the event had a thrust mechanism with a dip angle of 32° on the southward dipping plane.

Figure 4 displays the distribution of aftershocks until 30 days after the main shock (until January 11, 1993), as located by the USGS. It suggests that the fault plane lies between the epicenter near the Cape of Batumanuk and the Cape of Bunga, on the northeastern tip of Flores Island. The length of the fault is about

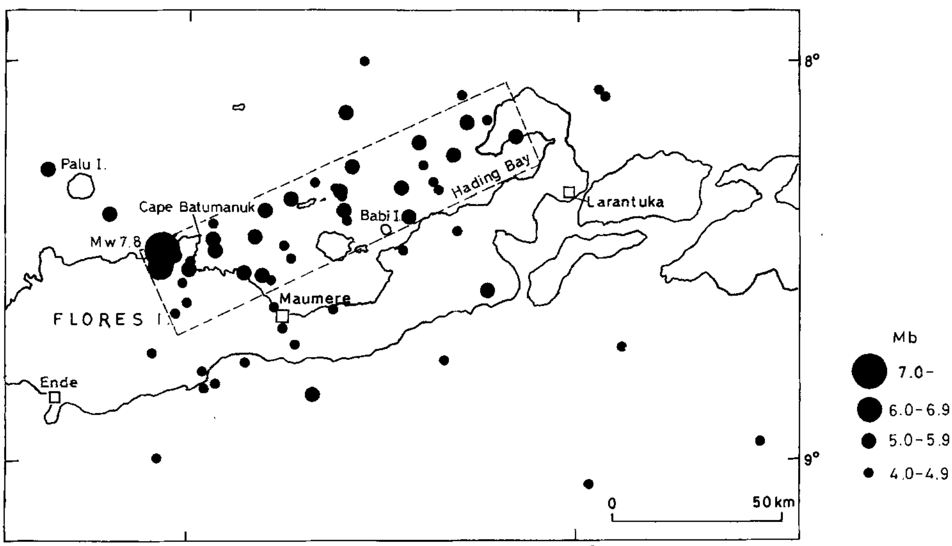

Figure 4
Distribution of aftershocks until January 11, 1993, that is, thirty days after the main shock from USGS. Dashed rectangle shows the area of the estimated fault.

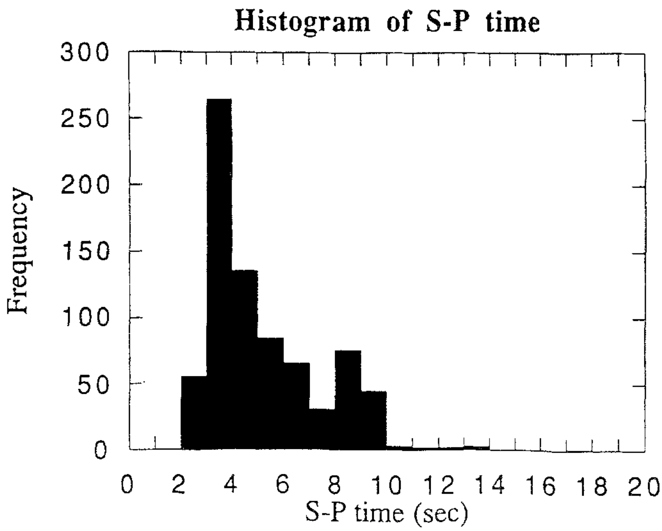

Figure 5
S-P time distribution of aftershocks from noon, December 30, 1992 to evening January 5, 1993 observed at the top of Broadcasting Tower Hill behind the residential area of Maumere.

110 km, and the horizontal width is 35 km. The fault plane area partially underlies the coastal regions near Cape Batumanuk and Cape Bunga, at the northeast end of Flores Island. Babi, Besar and Pomana Islands are estimated to be located above the fault plane area.

We temporarily observed aftershocks by setting short-period seismographs on a rock hill of the local TV station behind the residential area of Maumere City, from the afternoon of December 30, 1994 to the evening of January 5, 1993. During this period, about 1,000 aftershocks were recorded and S-P times were estimated for 773 events. Most of the S-P times of the events are distributed between 2 and 10 seconds (Fig. 5), indicating the occurrence of most aftershocks within 80 km of Maumere City. As it is well-known that the tsunami source area coincides generally with the aftershock area, we can judge that the tsunami source area also extended close to the north coast of Flores Island.

Coseismic crustal deformation was observed by inhabitants at several points in the coastal villages, and we generated a map of the distribution of vertical displacement shown in Figure 6. The shore line was uplifted on the coast west of Cape Batumanuk by 0.5 to 1.1 meters, and subsided at many places east of the Cape. The amount of subsidence reached 1.6 m at Kolisia village, 25 km northwest of Maumere. Evidence of subsidence can also be seen in the port area of Maumere. However, here liquefaction took place, making it difficult to distinguish the amount of subsidence purely due to coseismic crustal deformation. The subsidence on the shore of Babi Island was also observed by an eyewitness to be 75 centimeters.

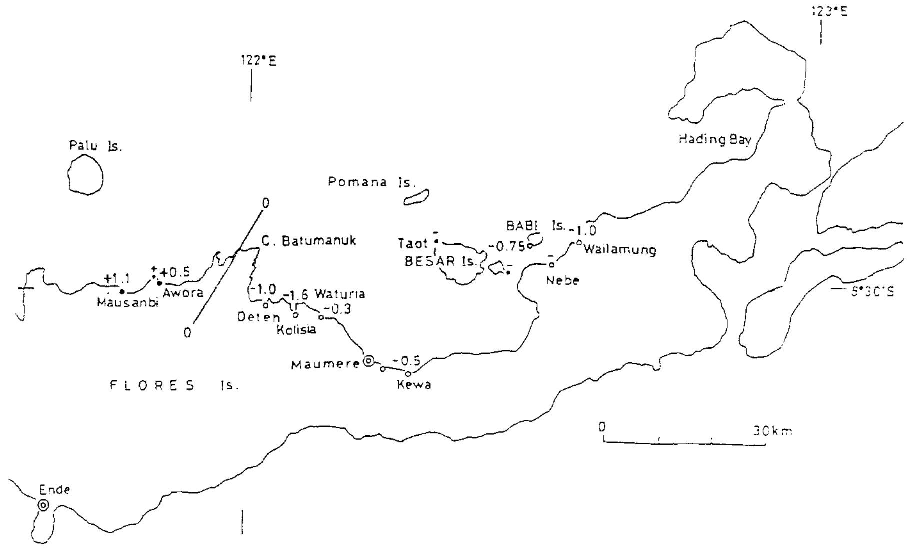

Figure 6
Distribution of vertical crustal deformation in meters. Positive values show uplift, while negative ones show subsidence.

Based on eyewitness accounts, the tsunami arrival times after the main shock at most of the coastal villages were distributed between 2 and 5 minutes. We back-projected the tsunami propagation from the observation points, and the result is shown in Figure 7, which also suggests that the tsunami source area was located close to the north coast of the eastern part of Flores Island. We also notice that the tsunami arrival time was observed as only 2 minutes, even in Hading Bay.

3.2 Distribution of Seismic Intensity and Damage

The seismic intensity on the Flores Island region was presented by the Meteorological and Geophysical Agency of Indonesia as shown in Figure 8. Seismic intensities on the MM scale were estimated as 9 to 10 at Maumere and 8 to 9 at Ende on the southern coast of Flores Island. Most of the brick houses were damaged in both cities. Small and moderate size landslides and rock falls appeared throughout the mountainous regions of those districts. Traffic on the 147-km long highway between Ende and Maumere was blocked for more than one month.

The earthquake was felt at Ujung Pandang (MM intensity 4) on Sulawesi Island, Kupang (3) on Timor Islands, Waingapu (4) on Sumba Island, and at Bima (3) on Sumbawa Island. It was also felt at Denpasar (2) on Bali Island, 700 km west of the epicenter.

The Military Commander of Maumere identified the areas of most severe damage due to the earthquake and initiated relief efforts. Hatched zones in Figure 9

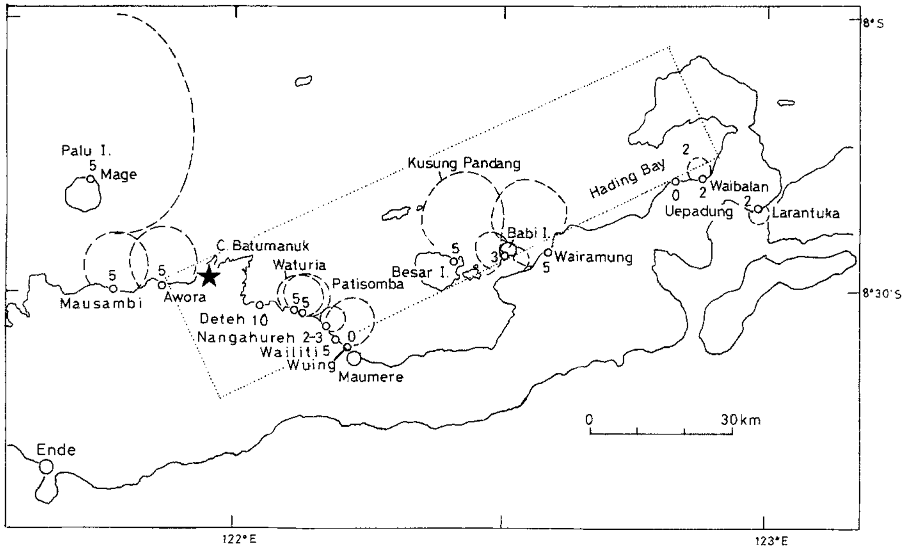

Figure 7
Tsunami arrival time (minutes) after the earthquake in minutes. Broken line circles show the inversely drawn refraction lines of tsunami propagation. Dotted area shows the location of the estimated fault by the aftershocks in Figure 4.

show the damaged areas for both the earthquake and the tsunami. As tsunami damage occurred only on the coast of the Flores Sea, the damaged areas on land and on the south coast are purely due to the earthquake. Arrows on the north coast of Flores Island indicate places with only slight damage due to the tsunami. Tsunami damaged coast extended as far as Reo Port on the western part of Flores Island.

Damage to public constructions and buildings was reported in detail by HAKUNO (1993) and SHIBUYA (1993).

4. *Tsunami Heights and Damage in Coastal Villages*

4.1 *Field Survey of the Tsunami*

We conducted a field survey of the tsunami damaged coast on the eastern part of Flores Island from December 29, 1992 to January 5, 1993. We divided our members into four teams, who visited about forty coastal villages to determine seismic intensity, crustal movement, tsunami arrival time, and inundation area. In addition, we also asked whether they had correct knowledge of tsunamis. We prepared questionnaires written in Indonesian, and asked Indonesian translators to conduct interviews at each coastal village.

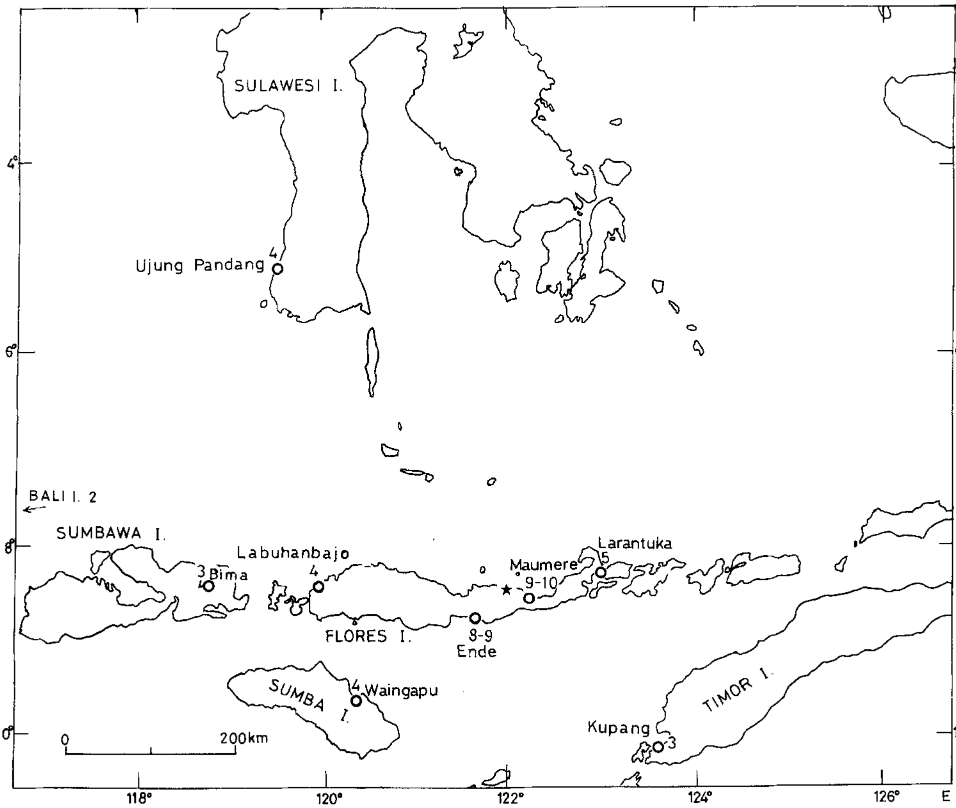

Figure 8
Distribution of seismic intensities on the Modified Mercalli scale.

On January 3 and 5, we were given the opportunity to ride in helicopters of the Indonesian Air Force, and we visited Ende, Palu Volcanic Island, and the coast of the northeastern tip area of Flores Island.

As there are no benchmarks on the coast, we measured tsunami height above sea level at the time of the survey. The astronomical tide components at tsunami damaged villages were corrected, resulting in values of tsunami heights above the mean sea level. In order to check how the numerically predicted astronomical tide agrees with the actual one, we made observations of sea-level change on New Year's Day, 1993 at the Sari Beach Hotel for calibration, and confirmed that they agree well. Astronomical tide change on the day of the tsunami is shown in Figure 10. At that time, sea level was higher than mean sea level by 24–36 centimeters.

Figure 11 shows the locations of surveyed points with evident damage. We surveyed approximately 40 points, but little damage occurred on the coasts between Maumere and Talibura, 30 kilometers to the east, thus only the measured heights will be described at these locations.

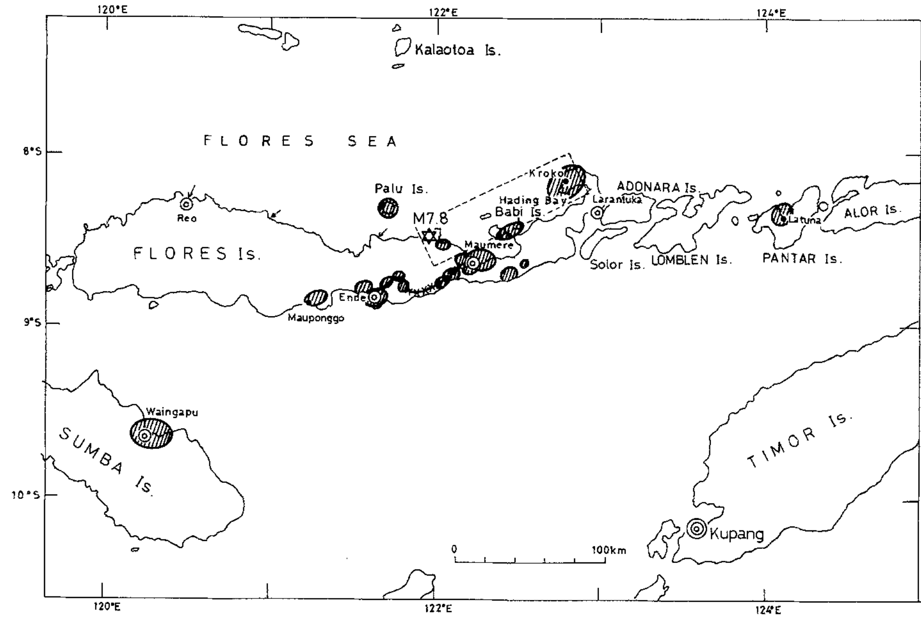

Figure 9
Damaged areas (hatched zone) identified by the Military Commander of Maumere.

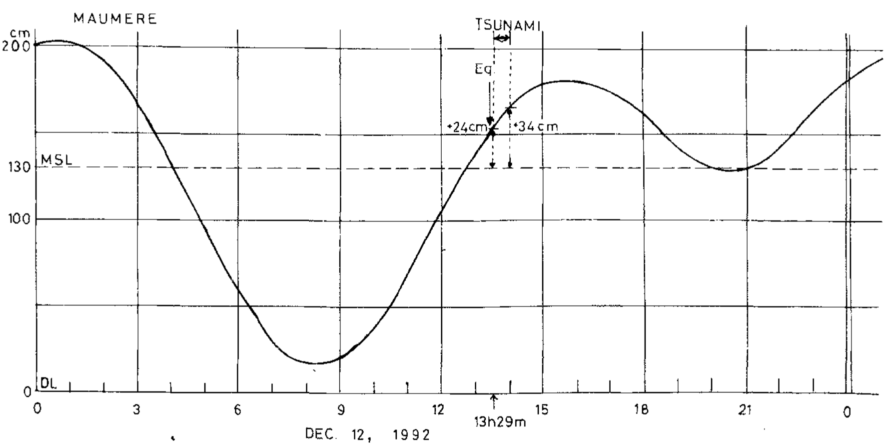

Figure 10
Astronomical tide at Maumere on the day of the 1992 Flores earthquake. The first tsunami wave arrived at the coast in the source region at tide stage of 24–36 cm above mean sea level.

4.2 Tsunami Damage at Maumere Port

Evidence of severe liquefaction was observed in the Maumere Port area. A line of large cracks could be seen on the ground in front of the market yard (Fig. 12).

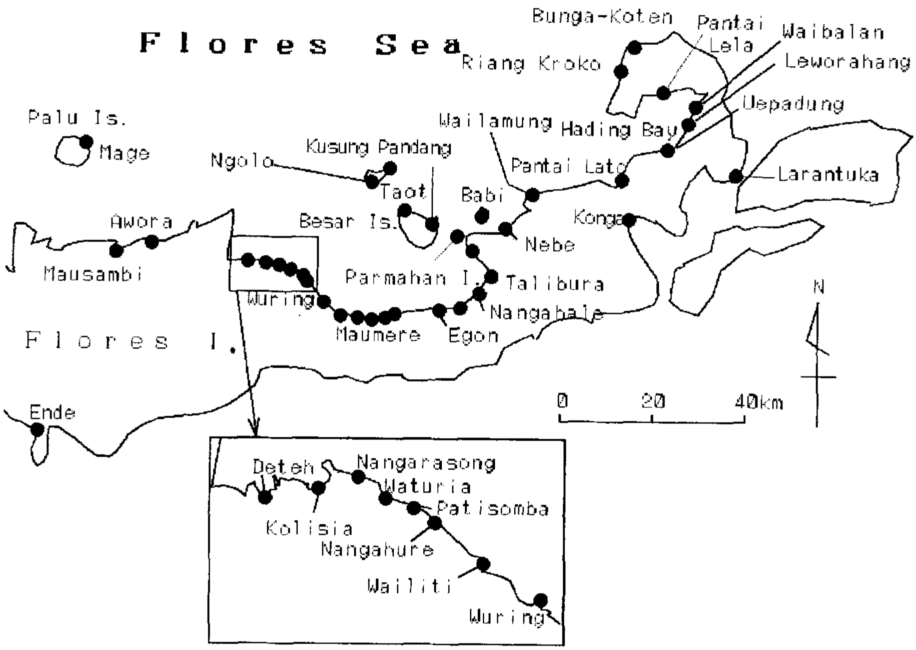

Figure 11
Locations of surveyed villages.

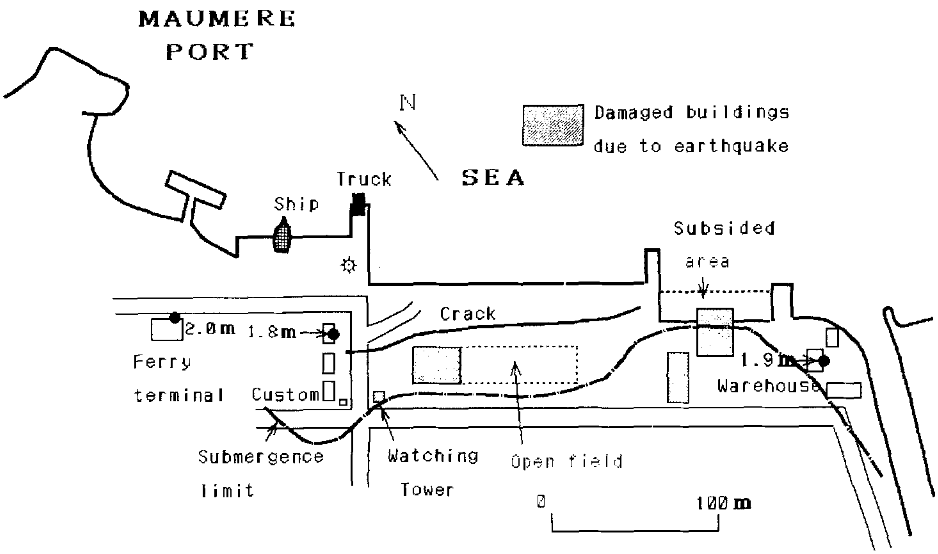

Figure 12
Inundated area of Maumere Port. The broken line shows the limit of sea-water inundation. Numbers show the tsunami height above mean sea level (m). The locations of a displaced truck and a boat are noted, as well as the portion of the port which was observed to have subsided.

The ground evidently subsided by 0.5–1 m in this area, however we could not distinguish whether this was caused by crustal deformation or by liquefaction of the soil.

Sea water invaded the end of the front row of blocks and a clear high water mark could be observed. We measured the height of the water mark on an outside wall of the port office building as 1.8 m (after compensations for the astronomical tide component at the time of the measurement). The water mark was 0.6 m above the ground. Although buildings were submerged, tsunami damage was minor at Maumere. A truck in a parking lot was carried by the wave onto a pier, and a ship was washed onto a street along the waterfront (Fig. 12). A resident stated that the depth of the port area changed from 9–15 m at a point 20 m away from the sea wall (see Fig. 12).

4.3 Tsunami Heights and Damage on the West Coast of Maumere

(a) Wuring Village

The residential area of Wuring is on a spit about 3 km northwest of Maumere. The length of the spit is about 650 m. The main road runs on the axis of the spit, and the ground height is only 1.3–2.1 m above sea level.

Tsunami waves attacked the area four times, and the first wave came just after the main shock. Prior to the first wave, sea level dropped slightly. The first wave originated from the north and east directions. The second wave was the strongest and was accompanied by a loud noise. The third wave was the highest.

On this sand spit about 1,400 people had been living in houses built on stilts. Most of the wooden houses collapsed, and 87 persons were fatalities of the tsunami. The distribution of inundation height, and sea-water thickness above the ground are shown in Figure 13. The tsunami height was only 1.8–3.6 m above the mean sea level, and water height above ground was as much as 1.7 m maximum.

Most houses in Wuring were destroyed. The majority of the destroyed houses leaned towards the southeast, indicating flow from the northwest direction. The mosque, a concrete building, was only submerged and not destroyed. Traces of three water levels were visible on the wall at heights of 0.91, 1.91, and 1.56 meters, respectively. MATSUTOMI (1993) analyzed these traces in detail, and estimated the fluid speed as 2.7 to 3.6 m/s from west to east, with the resistance force required of the building calculated as 8.0 to 10.8 tons. He also estimated the force applied to a wooden pillar 15 centimeter square and one meter in length as 57 to 100 kilograms. Many wall supports of houses on stilts could not resist the horizontal force of the flow of sea water. Diagonal bracing of walls and supports is recommended for this type of house.

The coral reef is wider at the tip of the spit, and narrow at the landward side, consequently house damage was more severe at the landward side than that at the tip. At the time of the tsunami, many fishing boats drifted into the residential area,

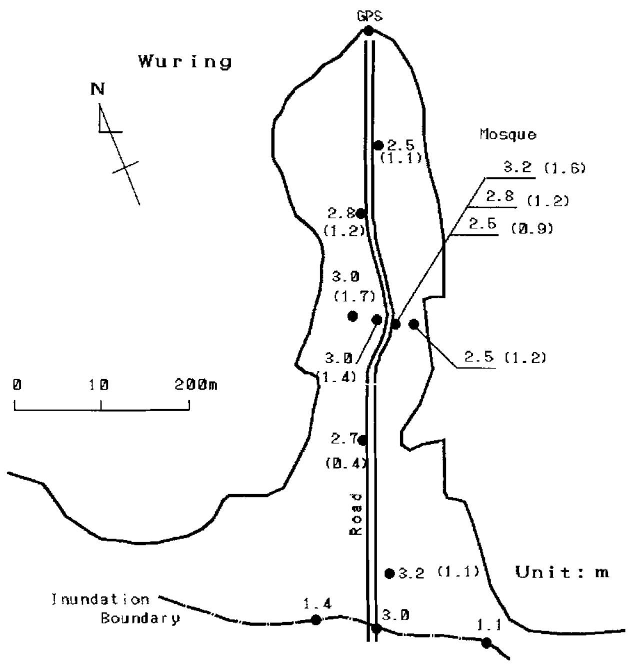

Figure 13
Distribution of tsunami heights (m) above mean sea level in the residential area of Wuring. Numbers with parentheses show sea-water thickness on the ground during the tsunami inundation.

which intensified the damage. The following day, the people made a bonfire of the rubbish. They did not carefully enough dispose of the embers, which led to a fire (the KOMPAS, Dec. 15) increasing the loss of property in Wuring.

(b) Wailiti, GPS 8° 35′ 16.2″S, 122° 11′ 02.8″E

Wailiti village is 5 km northwest of Maumere and the area inundated by the tsunami is shown in Figure 14. The first wave arrived 5 minutes after the earthquake. Six fishing boats were thrown on shore. The front wall of a factory was partially destroyed by the tsunami and a clear trace of inundated sea water was detected on the side wall of the building of 2.1 m height. One person was killed. The north coast of the river eroded and a new surface of sand step with a height of one meter appeared.

(c) Nangahureh, GPS 8° 34′ 18.3″S, 122° 10′ 14.3″E

Two or three minutes after the earthquake the first withdrawal of sea water was seen horizontally about 50 m. Sea water (not always being the first wave) broke the bank of a lagoon, whose fresh water became salty after the tsunami (Fig. 15). Sea water invaded a corn field reaching a height of 1.9 m. A crack line appeared on the field and white sand gushed into the cornfield near the crack.

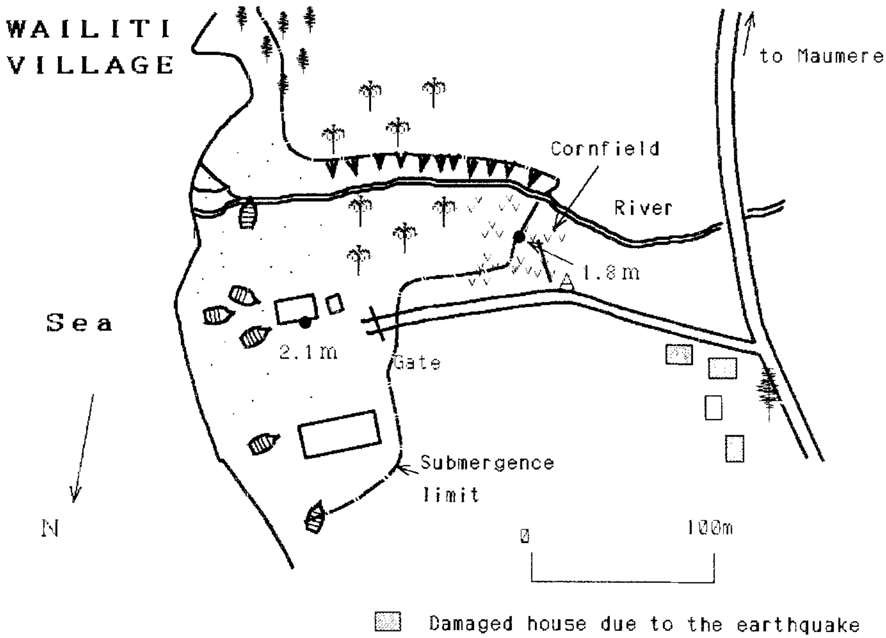

Figure 14
Inundation area in Wailiti village. A large crack appeared in the ground in the cornfield (A). Six boats were displaced on the sandy shore.

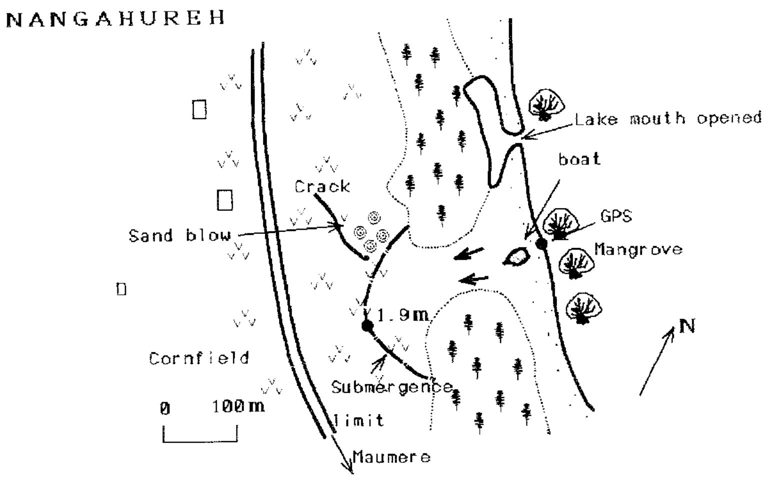

Figure 15
Inundation area in Nangahureh village. Sea water eroded the beach so that the lagoon became open to the sea. An eminent crack appeared on the ground of a cornfield, where sand blowing was observed. A boat was displaced on the sandy shore.

(d) Patisomba, GSP 8° 33′ 01.8″S, 122° 08′ 38.5″E

Strong shocks were felt twice within an interval of 15 min, and a long crack which measured 1 km appeared on the ground. The tsunami arrived 5 min after the shocks without lowering the sea level before the arrival of the initial wave. The wave front looked like a wall. Waves arose repeatedly with the first one incoming from the east. The waves inundated the area to 3.3 m, sweeping away four houses (Fig. 16).

(e) Waturia, GPS 8° 32′ 48.8″S, 122° 07′ 57.2″

The tsunami wave hit 3 times, the second one being the largest. Before the first wave, the shore line regressed by 200 m. The first wave arrived 5 min after the earthquake from the direction of Besar Island (ENE). Three houses collapsed in the village (Fig. 17). Due to the coseismic crustal deformation, sea-water level rose and the shore line shifted horizontally by 5 m inland. The amount of subsidence was measured as 30 cm vertically.

Water in the well at point A (Fig. 17) flowed better after the earthquake, while that at Waliki (the next village to the east) flowed insufficiently.

(f) Nagarasong, GPS 8° 32′ 24.8″S, 122° 07′ 14.9″E

The tsunami waves struck 3 times, and before the first wave sea water drew down and the sea bottom appeared. Subsequent inundation by sea water reached the foot of a mountain slope, where many rocks fell. Cracks with widths reaching 30 cm and gushing sand appeared on the ground (Fig. 18). Residents were jeopardized by both the tsunami and rocks falling from the steep mountain slopes.

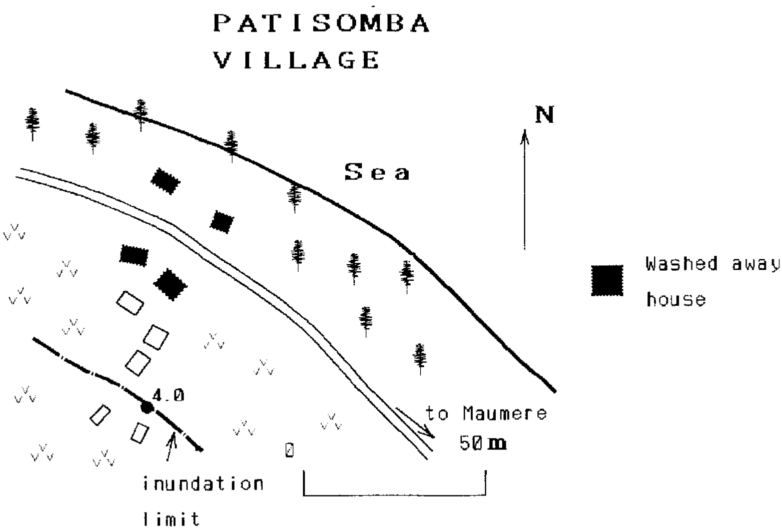

Figure 16
Inundation area in Patisomba village.

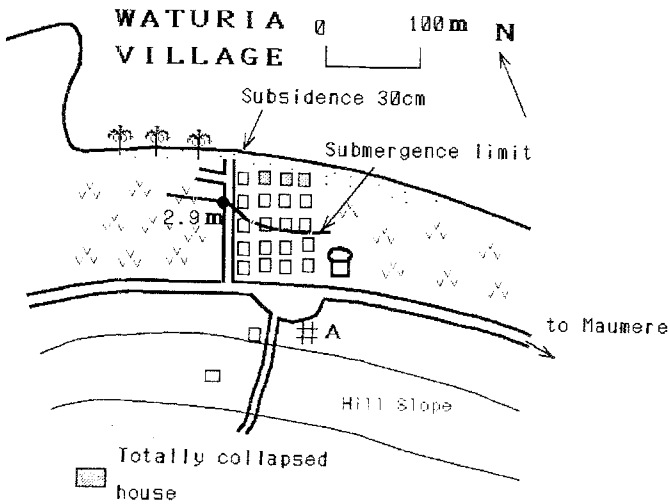

Figure 17
Inundation area in Waturia village.

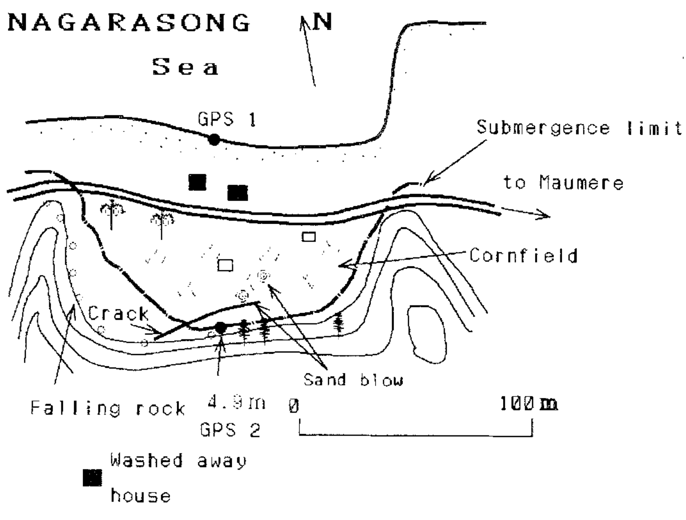

Figure 18
Inundation area in Nagarasong village. Rocks fell along the slope of the hill behind the village.

(g) Kolisia, GPS 8° 32′ 33.5″S, 122° 05′ 17.5″E

Sea water crossed the highway and flooded a rice field as much as 400 m from the shoreline. Maximum runup was 5.2 m. Earthquake damage was serious and 8 people were killed. The ground subsided 1.6 m and the beach became narrower (Fig. 19). A section of highway (1 km length) between the villages of Kolisia and

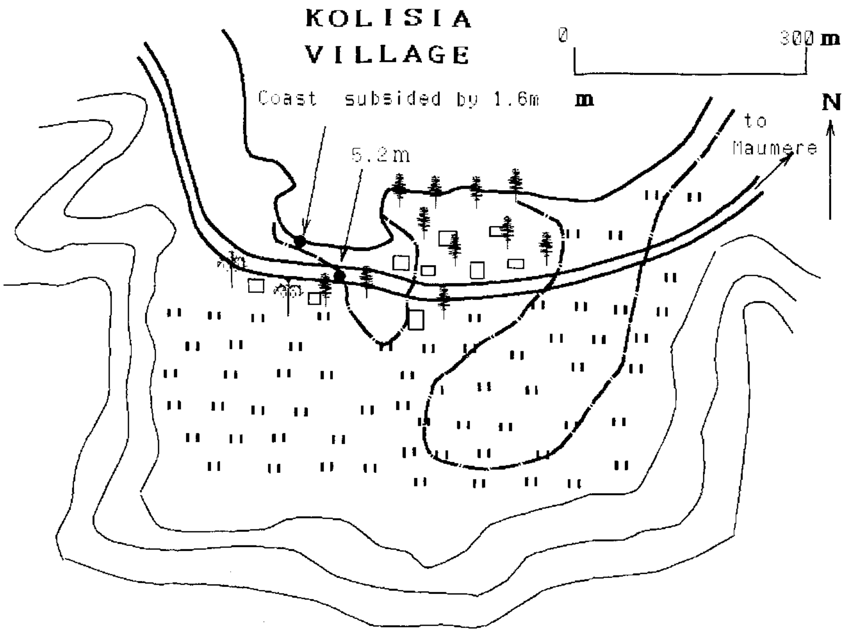

Figure 19
Inundation area in Kolisia village, where rice fields were flooded by sea water.

Deteh was seriously damaged due to the falling rocks and collapsed shoulders of the road.

(h) Deteh in Magepandang village, GPS 8° 31′ 49.1″S, 122° 02′ 10.6″E

Five to ten minutes after the earthquake, the first of three waves struck. The third was the highest, and the second one was the smallest. Maximum runup was 2.3 m. Sea water submerged most of the residential area of the village and a few houses were destroyed (Fig. 20). This inundation claimed two lives.

The shore line moved landward by 4 m and the width of sandy shore narrowed to only one or two meters due to the subsidence of the ground by about one meter.

The highway across the Batumanuk Cape area leads to Arowa and Mausambi villages. However, we could not reach those villages by car because traffic was interrupted by landslides and rock falls in this mountainous region. We were forced to navigate the Batumanuk Cape by boat on January 2, 1993.

(i) Awora, GPS 8° 29′ 36.2″S, 121°51′ 08.5″E

Awora village is located 20 km westward of Deteh beyond Cape Batumanuk. There is a small cape some 500 m west of the village, and a rock there appeared above the sea. People in the village said that the rock emerged above sea level after the earthquake. The ground seemed to be uplifted about 50 cm by eye measurement of the rock. The split of the coral reef on the east end of the village became wider, caused by the uplifting of the ground (Fig. 21). The tsunami arrived here 5 min

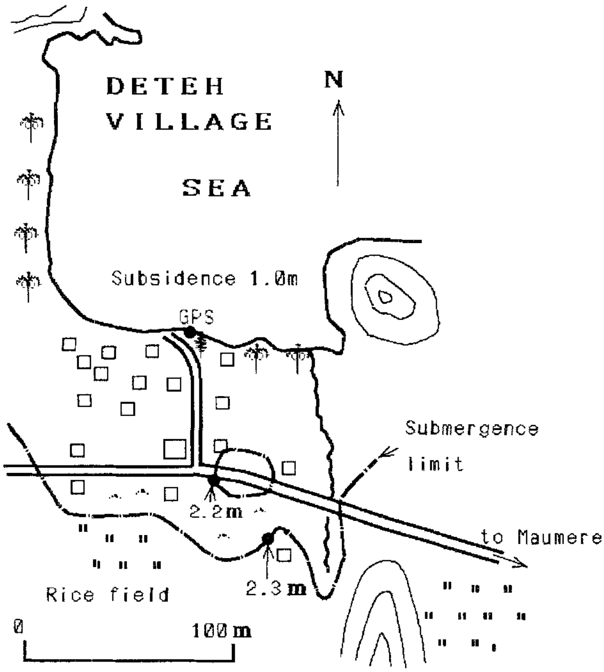

Figure 20
Inundation part of the residential area of Deteh village in the Magepanda region.

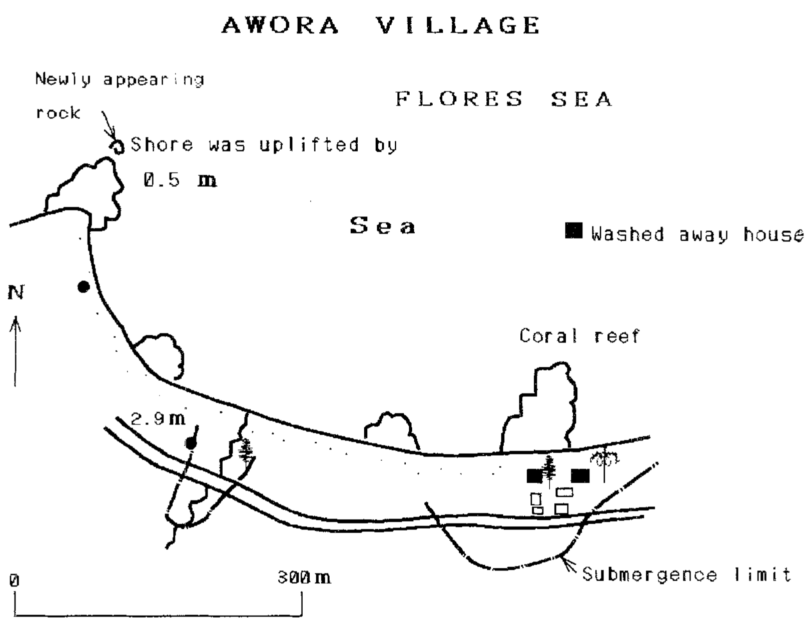

Figure 21
Tsunami damage in Awora village.

after the earthquake and runup was 2.9 m. Several houses on the coast were swept away and one person perished.

(j) Mausambi, GPS 8° 30′ 34.1″S, 121° 47′ 10.1″E

The tsunami arrived 5 min after the earthquake. Before the first wave arrived, the sea withdrew. Three waves arrived, the second being the largest. Sea water crossed the main road and invaded a rice field behind the residential area. In the residential area sea water rose up to the height of an adult's waist, 80 cm above the ground, that is 3.4 m above mean sea level. Two people were killed due to the tsunami.

Inhabitants said that another tsunami which besieged the village in 1973 exceeded the height of the present event. We could find no corresponding descriptions in any of the authorized tsunami catalogs mentioned in Chapter 2.

The ground was uplifted by 1.1 m on the shoreline.

(k) Mage (Palu Island)

Mage village lies on the northeast coast of the volcanic island of Palu. After the earthquake, sea level gradually subsided and five minutes later the first wave forming a wall of water attacked the village from the north. The initial wave regressed about 20 min before the arrival of several other waves. The first one was the largest. Sea-water inundation reached a stone wall surrounding the field of the elementary school, where runup was as large as 2.8 m.

4.4 Tsunami Heights and Damage on the Shores of Islands North of Flores Island

(a) Ngolo village on Pomana Besar Island

There are more than 50 houses in Ngolo village on Pomana Besar (Big) Island. Within the residential area evidence of liquefaction was observed on the ground. During the earthquake, numerous cracks and water spouts appeared, and many houses were destroyed by shaking. Soon after the earthquake a wall-like tsunami wave attacked the village. There were five waves of which the first one was the highest. Water withdrew by 20 m between waves.

The entire residential area of the village was submerged and tsunami height was measured at 2.7 and 3.2 m (Fig. 24). The ground height was 2.0 m in front of the Mosque, located in the central part, thus the covering thickness of the sea water was about 1 m in the residential area.

Prior to the earthquake, fish which usually live in the deep sea died and floated on the sea surface. One week before the earthquake inhabitants easily caught many deep sea fish in the shallow sea region.

Twenty-five persons lost their lives on Pomana Besar Island, including Buton.

(b) Buton on Pomana Besar Island

A clear trace of sea water remained on the wall of a house, 74 cm above the ground from which we established the tsunami height as 1.5 m.

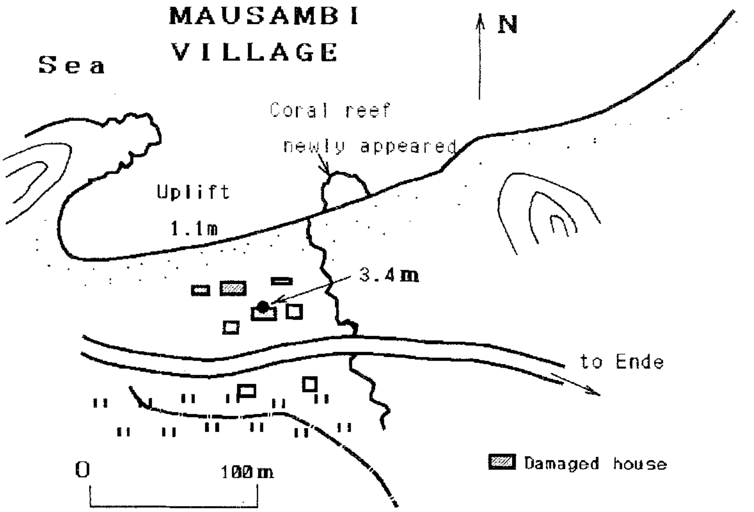

Figure 22
Inundation area in Mausambi village.

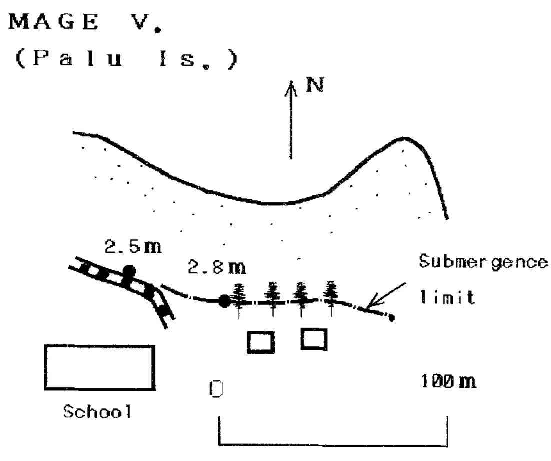

Figure 23
Inundation area in Mage village on Palu volcanic island.

(c) Taot on Besar Island, GPS 8° 25″ 30.7″S, 122° 20′ 09.3″E

Taot village is located on the northwest coast of Besar (Big) Island where 5 families totalling 66 persons reside (Fig. 25). The tsunami height reached 2.8 m causing minor wave damage. The Mosque collapsed due to shaking.

Subsidence is indicated by the submergence of the bases of trees below high-tide level.

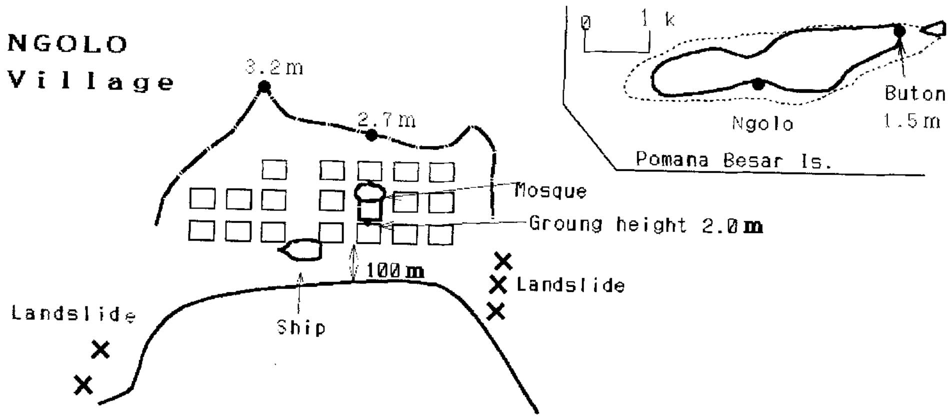

Figure 24
Inundation area of Ngolo village on Pomana Besar Island.

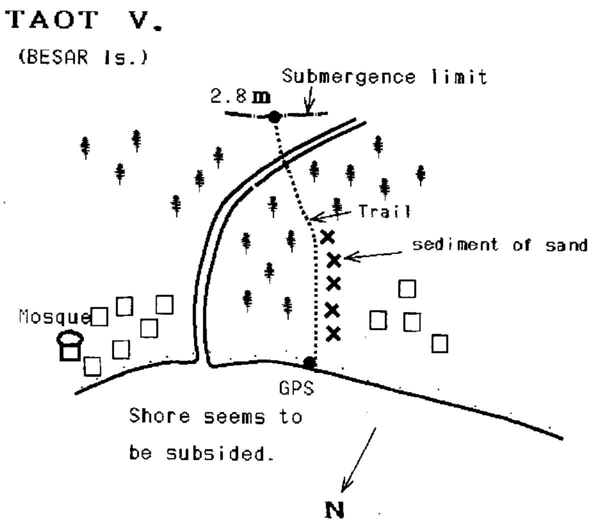

Figure 25
Inundation area of Taot village on the west coast of Besar Island.

(d) Kusung Pandang on Besar Island, GPS 8° 26′ 48.4″S, 122° 24′ 32.1″E

Kusung Pandang village is located on a small bay on the northeast coast of Besar Island (Fig. 26). In this village 55 people comprising 11 families lived, but no one was killed. Several people were carried away by the tsunami waves, but all were rescued. The tsunami wave arrived at the coast as a wall of water. Three waves arrived, with the initial one appearing five minutes after the earthquake. Sea water ran up along the gentle slope and reached a height of 4.1 m, 180 m inland from the

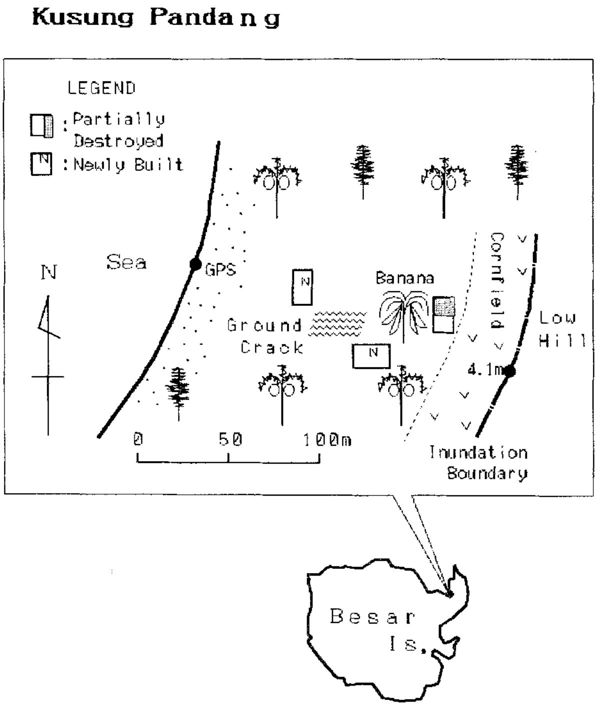

Figure 26
Inundation area in Kusung Pandang village on Besar Island.

shore line. The ground was cracked and fissured locally. Most houses on stilts were damaged severely or slightly due to both the earthquake and the tsunami waves.

(e) Pangabatang Island

There are two islands between Besar Island and the mainland of Flores Island; the western one is Damhilah Island and the eastern one is Pangabatang Island. The latter is a flat small island with a length of about one kilometer, part of which was "lost" as a result of the tsunami. The portion which disappeared had been a sandy beach.

4.5 Tsunami Damage on Babi Island

Babi Island is located approximately 40 km northeast of Maumere city. It is a round island with a diameter of 2.5 km, and is surrounded by a coral reef. A mountain of 351 m elevation was in the center of the island. There is no flat land on the coast except for the south coast facing the coast of Nebe (Nanga Merah) on the mainland of Flores Island. The width of the strait between Babi and Flores islands is about 5 km. Two villages are situated on the flat land of the southern coast: a Muslim village (Kampungbaru) on the western side and a Christian village

(Pagaraman) on the eastern part. The coral reef is considerably narrower on the south coast, where the two villages are situated, than it is around other parts of the island. The population of the island was 1,093 and the ratio of populations of Muslim to Christian villages is 5 to 1.

The number of dead and lost persons on Babi Island was announced by journalists as 600 to 700 within a few days after the catastrophe, but after the refugee camp was constructed at Nangahale on December 17, several hundred temporarily 'missing' persons were recovered in the camp, and the exact number of victims finally given on January 4, 1993 as 263 persons.

On Babi Island the number of women (175) killed was more than twice that of men (88). This tendency can be also found in other tsunami events. For example, TSUJI and HINO (1993) pointed out the same tendency in coastal villages on the Kumamoto Prefecture, Japan, in the case of the Ariake Bay Tsunami of 1792. As a result of our interviews in the field, we found that men have a tendency to take refuge for themselves, but women want to protect small children and the elderly during an emergency. This difference in motivation may affect the number of tsunami victims.

(a) Muslim village (Kampungbaru) on Babi Island

The residential area of the Muslim village, Kampungbaru, faces the sea and a row of palm trees were located along the shore fronting the village. These provided virtually no protection for the houses behind. All the houses were uprooted from their original locations and the materials of the houses, furniture and other goods were carried into the palm tree forest behind the village. The Mosque was completely washed away, leaving only the roof on the ground. The ground in most of the residential area was covered by coral sand, which was brought in by the tsunami waves.

We measured the inundation height by the traces on tree bark. Tsunami height was 3.6 m at the eastern point of the residential area of the Muslim village. The JAPAN DISASTER RELIEF TEAM (1993) also measured tsunami heights at 5 points in the residential area, and determined the heights between 3.28–3.68 m above MSL. YEH *et al.* (1993) reported tsunami inundation slightly higher (4.6 m) than our result. The ground height was only 1.2–2.0 m above mean sea level. Thus, the tsunami with a water thickness of only 2 m entirely washed away the houses. The speed of the sea water is estimated to have exceeded 5 meters/seconds or more.

We also measured the tsunami height at 7.2 m at two points on the foot of the steep mountain slope behind the palm tree forest, west of the residential area (Fig. 27). No houses stood in front of the measured points. We assume that the actual height of the tsunami surface at the time of inundation of the residential area was about 4 m. The height of 7.2 m can be explained as a doubling of the height due to a reflected wave. The inundation height of 3.6 m can be explained as the height of a progressive wave after passing the high friction area.

As a result of interviews of survivors at the refuge camp at Nangahale, we learned that the tsunami arrived 3 min after the earthquake, and that the shore

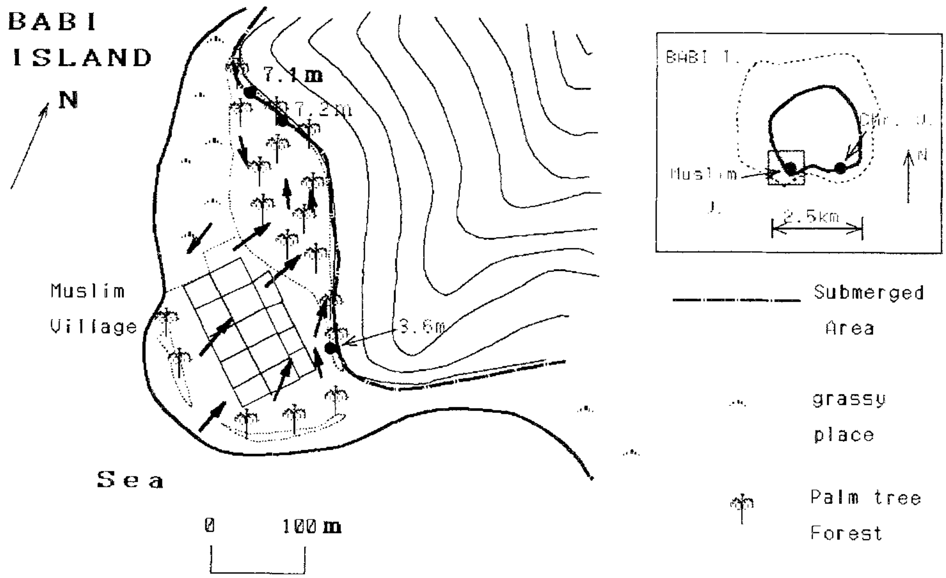

Figure 27
Inundation in the Muslim village (Kampungbaru) on Babi Island. Arrows show the direction of sea-water movement. Ground elevation of the residential area was about 2 m. Approximately 900 persons lived in the village. All the houses were swept away.

receded vertically by about 75 cm. Some witnesses indicated that the waves originated from the south, which would suggest that the waves which reflected from the mainland of Flores Island effected Babi Island more seriously than the direct waves from the source. On the slope of the mountain behind the village, rocks fell to the foot as a result of the earthquake, preventing inhabitants from evacuating from the tsunami.

(b) Christian village (Pagaraman) of Babi Island

The Christian village, Pagaraman is located on the southeast coast of Babi Island, directly facing Nebe village on the mainland of Flores Island. All houses in this village were swept away, and only foundations remained. Most of the residential area was surrounded by a palm tree forest, and the materials of the houses were carried into the forest (Fig. 28). Two lines of large cracks appeared on the ground of the grassy plain behind the forest (XX′ and YY′ in the figure). We easily detected the direction of tsunami flow by checking prostrated grass on the plain. Behind the grassy plain a sand dune 5 to 6 m high runs in an east-west direction, and sea water flowed over it. We could clearly trace the inundation height on the surface of palm trees and measured it as 5.6 m. Sea water surged across the dune and flowed westward along the valley behind. The ground height of the residential area was about 2 m, thus the thickness of sea water can be estimated as about 3 m.

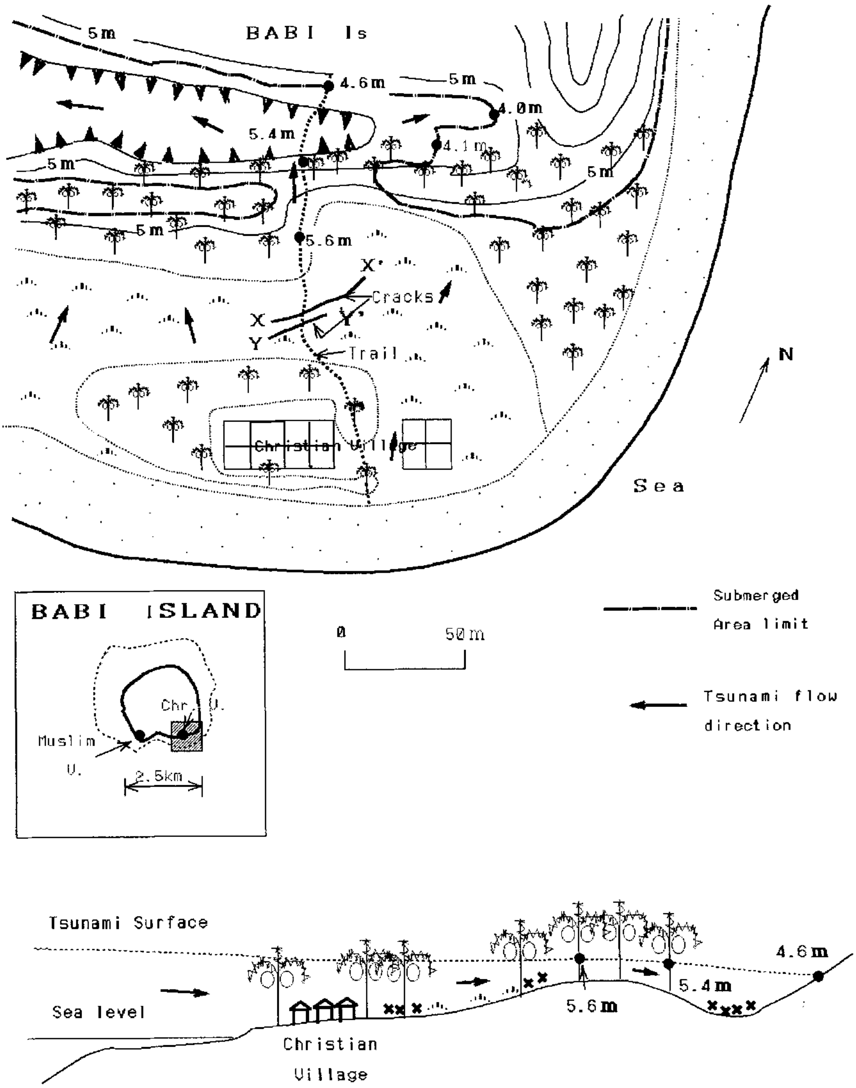

Figure 28
Inundation in the Christian village (Pagaraman) on Babi Island. Some 200 persons lived in the village. The ground height of the residential area is 1.5–2 m. All the houses were swept away. Crosses in the lower figure show sedimentation of coastal sand.

4.6 Tsunami Height and Damage from Nebe to Hading Bay

(a) Nebe (Nanga Merah) GPS 8°27′ 50.0″S, 122° 32′ 24.0″E

The coast of Nebe village is located on Flores Island facing Babi Island, separated by a channel 3 km wide. The residential area of Nebe is located within a palm tree forest and the ground elevation is 1.7–2.6 m (Fig. 29), and was inhabited

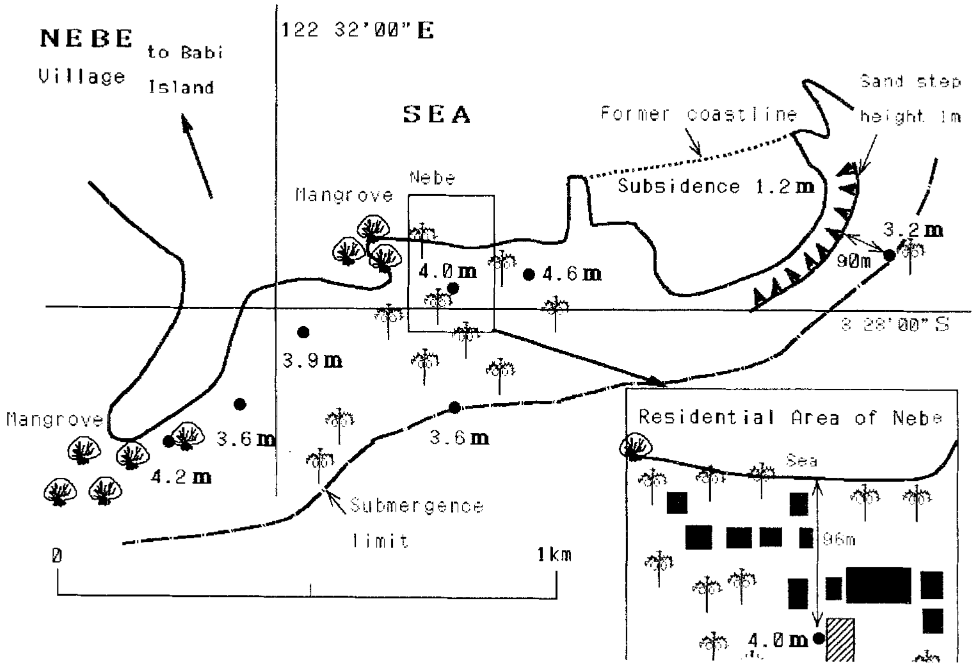

Figure 29
Inundation area of Nebe village and its vicinity.

by 35 families of which two elderly persons were killed by the tsunami. The first wave came 5 min after the earthquake (2 min according to another witness), and began with a regression of the shoreline by 200–300 m. Three waves came of which the first was the largest. One person noted that the shoreline shifted landward by 15 m compared to that before the earthquake. The crust also subsided there. Most of the houses were constructed of brick, and totally collapsed from the impact of the earthquake and the tsunami. The tsunami inundation height in the residential area was measured by the trace on the bark of trees to be 4.0 and 4.6 m. Sea water reached a point 320 m inland from the shoreline, where the height was 3.2 m. Cracks and gushings of sand appeared on the ground in the tsunami submerged area. Some traces of gushings were not disturbed by the flow of sea water, and they seemed to be formed by aftershocks.

We should note that only two persons of about 150 inhabitants were killed, despite the fact that most houses were totally destroyed. This suggests that the palm tree forest was effective in dissipating the tsunami energy, mitigating the human toll.

(b) Wailamung, GPS 8° 25′ 29.4″S, 122° 35′ 22.0″E

The entire residential area was surrounded by a palm tree forest inhabited by about 600 persons; 6 lives were claimed by the tsunami. The first wave arrived 5 min

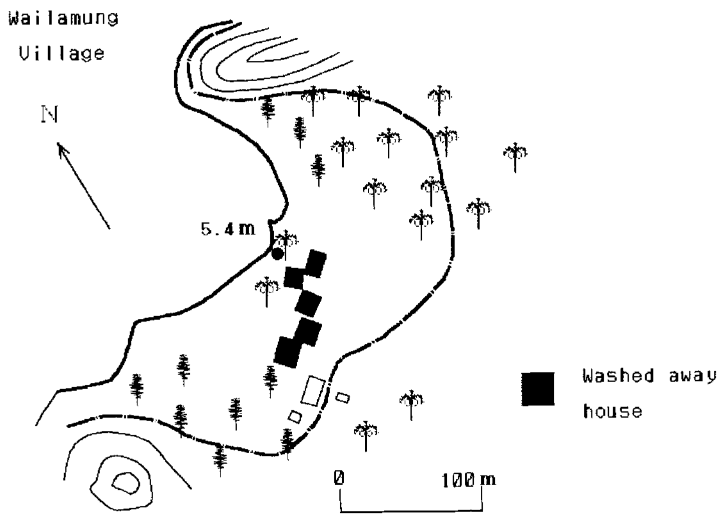

Figure 30
Inundation area in Wailamung village.

after the earthquake. The shore line subsided and shifted 10 m inland. The amount of vertical subsidence was measured as 1.0 m. The sandy shore was narrowed after the earthquake. The tsunami inundation height was 5.5 m, measured from the trace, where sea weeds were carried on a palm tree near the shore (Fig. 30).

(c) Pantai Lato, GPS 8° 21′ 20.0″S, 122° 46′ 05.5″E

Pantai Lato (= Lato Coast) lies on the southern coast of the mouth of Hading Bay. The submerged area is shown in Figure 31. The paved coastal road was obstructed by a crack at the southwest end of the village. A large-scale landslide occurred at the northeast coast of the village, burying the road there. Sea water did not reach the main road (further inland), and the submerged area covered about half of the sea-side residential area (Fig. 31), where tsunami height was measured at 3.5 to 3.8 m. Damage to houses was caused mainly by the earthquake. The numbers of completely and partially collapsed and inclined houses in the sea-side area were 12, 8, and 3, respectively. Only three houses were undamaged.

About 2–3 km southwest of the village the width of the submergence zone due to the tsunami reached 140 m from the shoreline. We measured a tsunami height of 6.9 m at this point GPS 8° 21′ 30.9″S, 122° 45′ 57.1″E (Fig. 32).

(d) Uepadung, GPS 8° 17′ 42.6″S, 122°49′ 56.8″E

Uepadung is located on the south coast of Hading Bay. The coastal road was lost due to the regression of the coast line. The top of a palm tree was seen on the surface of sea, which established that a large-scale landslide of the coastal region occurred here; the land moved into the sea and the palm tree remained standing. Sea water flowed along a river to the level of 11.0 m above mean sea level. One person testified that the wave arrived immediately after the earthquake.

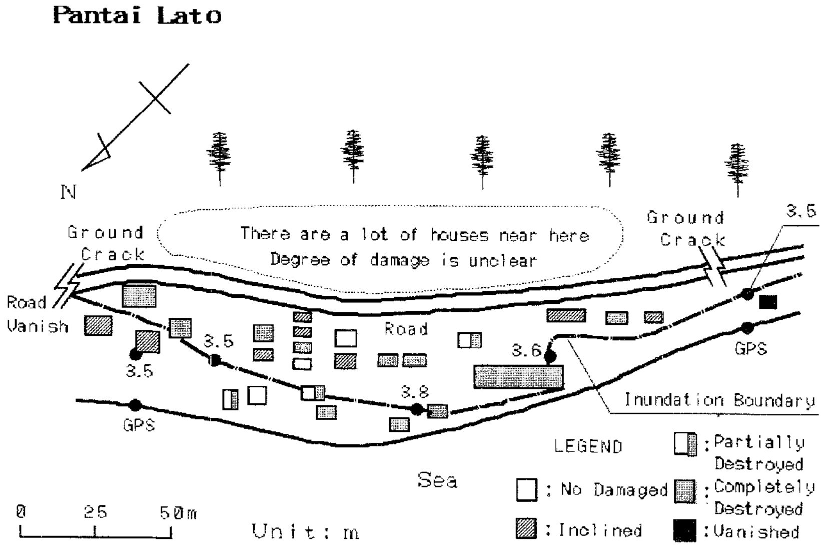

Figure 31
Tsunami submerged area and house damage due to the earthquake in the residential area of Pantai Lato.

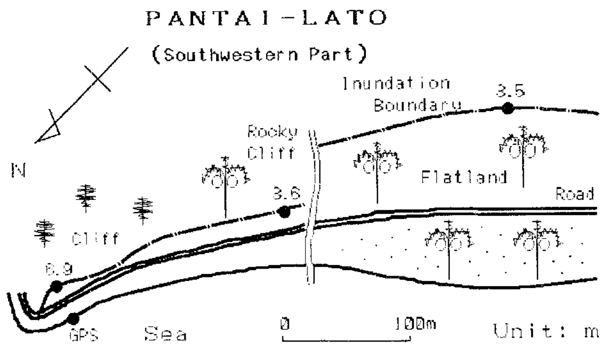

Figure 32
Southeastern part of Pantai Lato, about 2 km away from the main residential area shown in Figure 31.

(e) Leworahang, 8° 17′ 23.1″, 122° 52′ 39.2″E

Leworahang is located some 5 km east of Uepadung. The tsunami height was estimated by eye to be 10–14 m (Fig. 34). A palm tree moved into the sea area and stood there about 10 m apart from the shoreline with only its top appearing above the sea surface. The height of the tree was estimated at 12 m. It would appear that this was also the result of a landslide on the coast. YEH *et al.* (1993) reported that 12 houses were swept away and 24 people killed, and that near Lewobele, about 6 km west of Leworahang, at least two more subacueous slumps, about 1 km long each, were found.

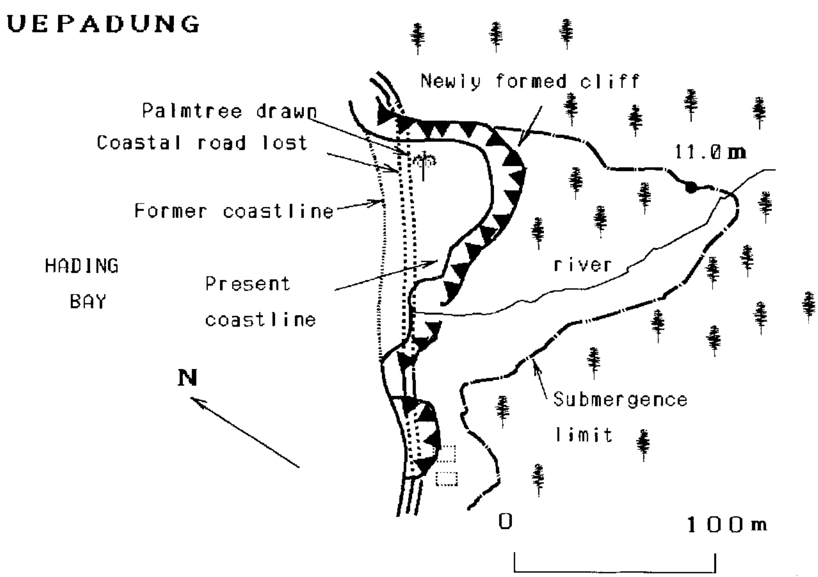

Figure 33
Shoreline regression and the inundated area of the coast of Uepadung village.

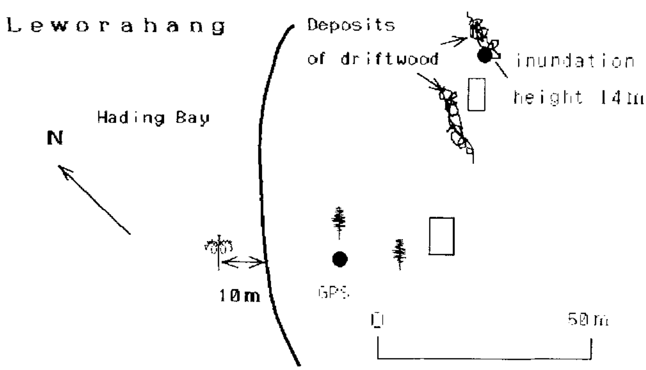

Figure 34
Tsunami inundation of Leworahang village.

(f) Waibalan, GPS 8° 16′ 51.9″, 122° 53′ 13.3″E

Waibalan lies on the coast close to the innermost point of Hading Bay. Tsunami waves arrived from the north three times. The first wave was the largest, arriving 2 min after the earthquake. The first wave looked like a white (or dark yellow) wall of water. The sea surface rose from the beginning without an initial draw. We measured two points on the submergence limits whose heights were 7.9 m (121 m from the shoreline) and 10.6 m (108 m from shore), respectively.

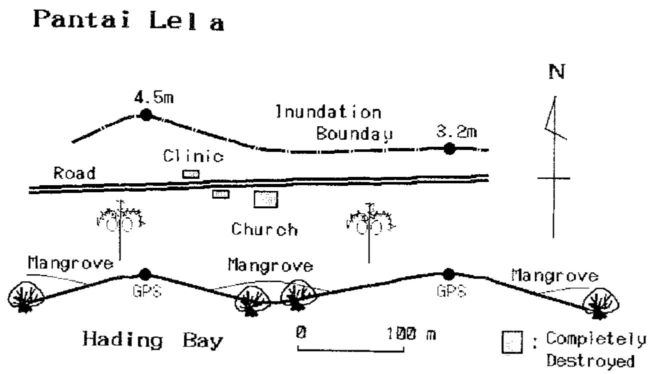

Figure 35
Inundation area of Pantai Lela village.

It is worthy of observation that the tsunami arrival time was only 2 min after the earthquake. If this is true, and taken together with the account of the witness at Uepadan that the tsunami arrived just after the earthquake, the origin of the initial wave should be within Hading Bay. This could have been caused by landslide(s) in the coastal area. That the water color of the first wave was white or dark yellow also indicates that some sea-water disturbance arose near the south coast of Hading Bay.

(g) Pantai Lela, GPS 8° 11′ 08.2″S, 122° 50′ 14.7″E

Pantai Lela (Lela coast) is located on a gentle slope on the north coast of Hading Bay. Tsunami waves arrived three times and the first was the largest, as a result of which the church building caved in (Fig. 35). In addition, two brick buildings were destroyed. The inundation height and length were 4.5 m and 140 m, respectively. The shoreline was shifted inland by 10 m which suggests subsidence of the crust.

4.7 Tsunami Heights on the Coast of the Cape of Watupajung

(a) Riang-Kroko (in Turubeang village), GPS 8° 09′ 01.4″S, 122° 47′ 0.03″E

An extraordinarily large tsunami hit the north and west coasts of the Cape of Watupajung. At Riang-Kroko village, sea water surged along the slope to a level of 26.2 m. Figure 36 displays the inundation area with tsunami heights at four points. YEH (1993) reported the average height of these values as 19.8 m. All vegetation was washed away in this area. In the residential area, with a ground elevation of 3.6 m, 69 families totalling 406 persons had lived in more than 200 houses, but no evidence of human life remained. Even foundations of houses were washed away. Here 137 persons lost their lives. Even large trees were uprooted. We could easily distinguish the inundation boundary due to the sharp color contrast of the ground; light brown soil for the submerged area, and green chlorophyll for the unsubmerged

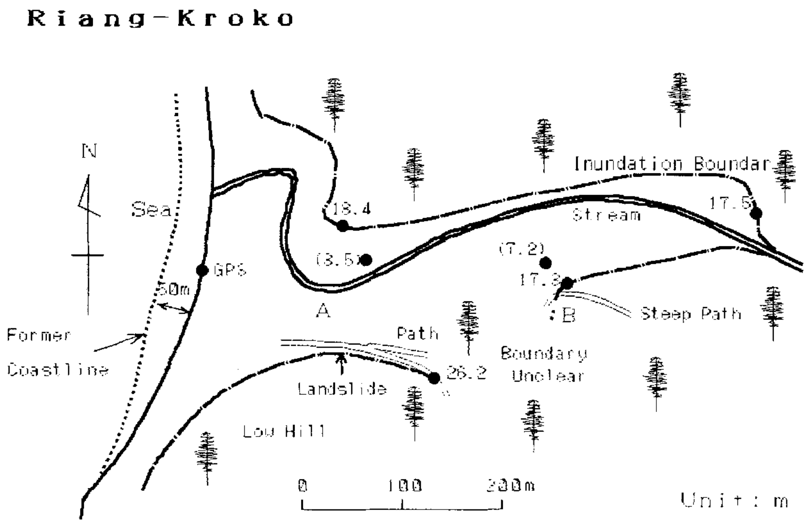

Figure 36
Inundated area in Riang-Kroko village, where 139 persons were killed due to the huge tsunami. Houses were entirely swept away and even foundations disappeared. No evidence of human life remained. No vegetation survived below the limit of the submerged area.

area. The tsunami waves struck five times and the first one was the largest. The coastline was shifted by 30 m inland. It is difficult to distinguish whether the shifting of the coastline was due to erosion by the tsunami or resulted from a landslide on the coast.

(b) Bunga-Koten (Bou Tanabeten), GPS 8° 06′ 40.6″S, 122° 47′ 44.3″E

We watched the coast between Riang-Kroko to Bunga-Koten on January 3, 1993 from two helicopters. The trace of inundation of the tsunami was clearly distinguished from the air because of the sharp contrast in ground color.

Bunga-Koten village is located 6 km northeast of Riang-Kroko. Here all 100 houses, one church, and the elementary school building were entirely swept away. The residential area here is called the colony (RT) of Bou Tanabeten (Fig. 37). On the ground, traces of the foundations of several houses could scarcely be detected. The tsunami height on the east slope was measured at 12.3 m. In contrast to such severe building damage, only three persons lost their lives here (KOMPAS, December 18).

4.8 Tsunami Height on the South Coast of Flores Island

Since the epicenter was located in the north coastal region of Flores Island, on the south coast of the island only minor evidence of the tsunami was observed by the native people.

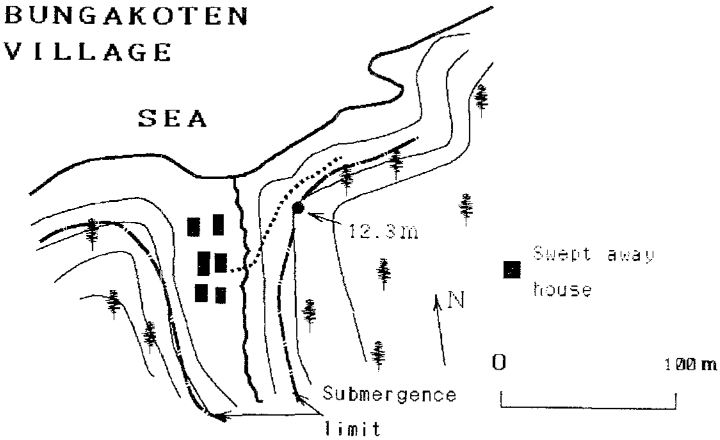

Figure 37
Inundated area of Bunga-Koten village (Bon Tanabeten). All one hundred houses were entirely swept away.

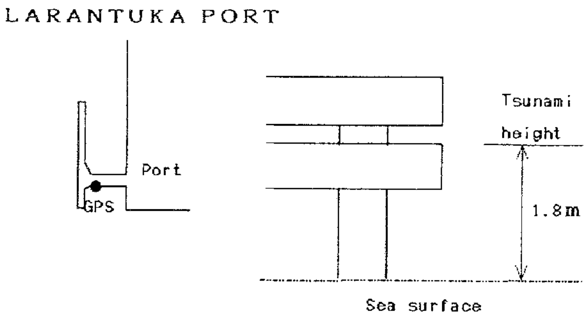

Figure 38
Sea water rose to 1.8 m above mean sea level at Larantuka Port.

(a) Larantuka Port

The earthquake was felt with an intensity of 5 on the MM scale at Larantuka Port, on the easternmost coast facing Adonara Island. Sea water rose to the upper edge of a concrete beam on the pier in the port, and it was measured 1.8 m high (Fig. 38). The tsunami was reported to have arrived only two minutes after the earthquake, and eight waves appeared within 5 min. The first wave was the largest, and sea surface gradually rose. It is difficult to explain such an early arrival and the short period of the waves. The possibility exists that the tsunami in this area was generated by a local landslide and was independent of the tsunami observed on the north coast.

No tsunami information was given at Waibalun Port (8° 20′ 42.5″S, 122° 56′ 58.9″E).

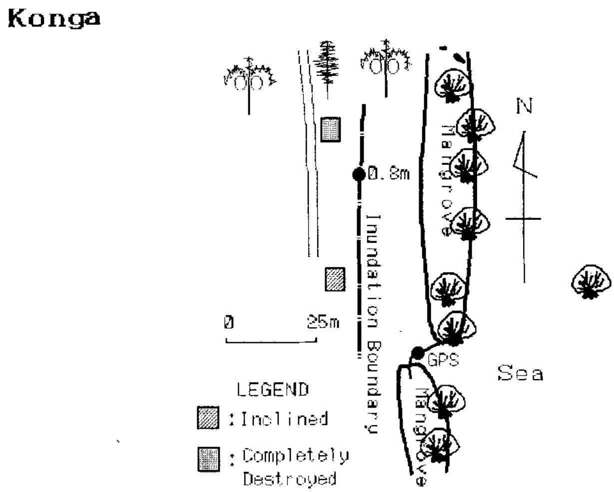

Figure 39
Inundation area at Konga on the southern coast of Flores Island.

(b) Konga, GPS 8° 26′ 36.5″S, 122° 47′ 04.8″E

Sea water inundated a width of 20–30 m from the shoreline, and many timbers drifted ashore. Evidence of a submergence limit could be detected by salt deposits on the sandy shore, which was corroborated by native people. The height at that point was 80 cm above the sea (Fig. 39).

(c) Ende

Ende City is located on the south coast of the central part of Flores Island. A sea-surface rise of about 50 cm was observed by the citizens.

4.9 Tsunami Evidence at Distant Locations

Kalaotoa Island is located about 150 km northwest of Maumere City and belongs to Selayar Regency in South Sulawesi Province. In the entire Selayar Regency, 19 persons perished and 130 houses were swept away resulting from the tsunami. Seventy of these houses were settled on Kalaotoa Island.

In Permana village on Buton Island, in Southwest Sulawesi Province 600 high floor houses entirely gave in or washed away and 3 persons were killed by the tsunami.

It is not clear whether the damage at Latuna on Pantar Island (see Fig. 9) was caused by the tsunami. Some tsunami damage was expected on the north coast of the Adonara and Lomblen Islands, but we could not observe this unambiguously.

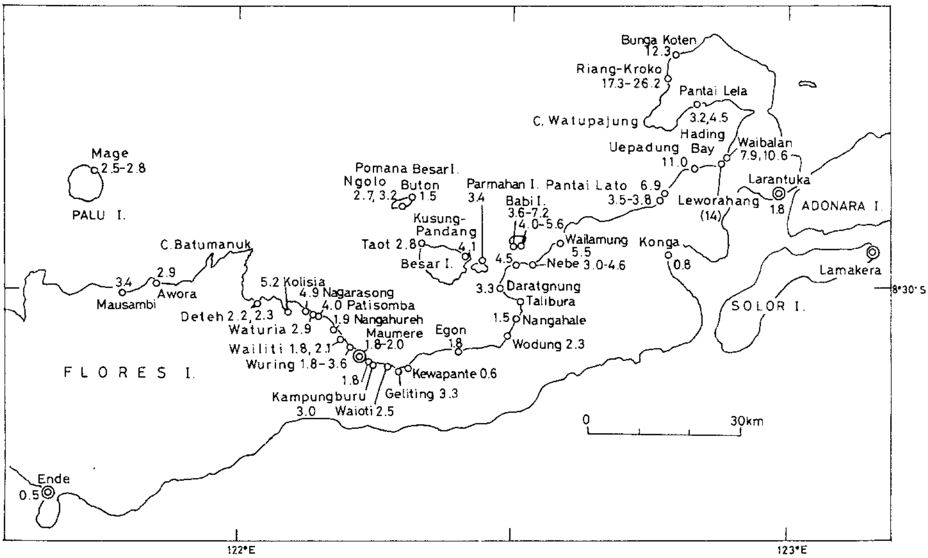

Figure 40
Distribution of tsunami heights on the coast of Flores Island. Numbers show runup height above mean sea level (m).

4.10 Distributions of Tsunami Heights

By using the result of our field survey we obtain a map of the tsunami height as shown in Figure 40. A clear contrast in the tsunami heights between the coasts west of Wailamung and east of Pantai Lato can be noticed. Tsunami heights on the western coast did not exceed 7 m, while those of the eastern coast generally exceeded 10 m. It is difficult to explain this variation in the tsunami height distribution simply by one fault model. It is probable that landslide(s) on the coastal area, and/or on the sea bed were the cause(s) of the huge tsunami heights observed on the eastern coast.

5. Human and House Damage

5.1 Statistics of Human and House Damage

In addition to our survey, we obtained statistics of human and building damage from the Military Commander of Maumere, and from the Sikka Regency Office at Maumere (see Appendix 2). These statistics are tabulated for each of the Regencies. In addition, we gathered articles describing the damage from the newspaper "Kompas", dated from December 13 to 31, 1992, in which reports of individual villages occasionally appeared. In addition to those accounts, we could use the

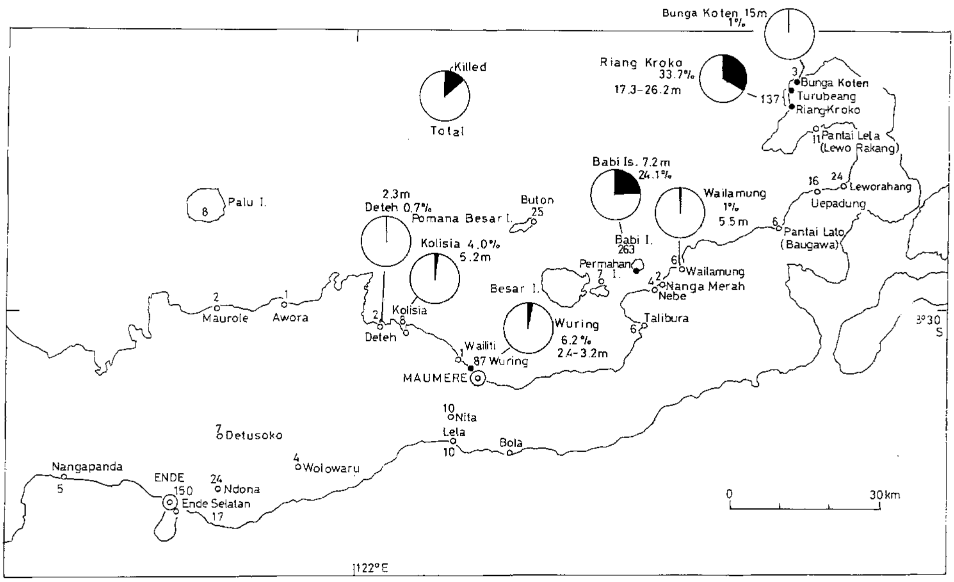

Figure 41
Numbers of deaths from the Flores Island earthquake and tsunami by villages. Mortality in seven villages struck by the tsunami is shown by circle graphs.

eyewitness accounts from our survey to help document the amount of damage and total number of houses and population in each village. Thus, we obtained the map for the distribution of the number of lives taken in the eastern part of Flores Island as shown in Figure 41. In Figure 41, numbers located inland and on the southern coast of Flores Island refer to victims of the earthquake, while those on the north coast are probably mostly of victims of the tsunami.

5.2. House Damage

The information regarding damage covers four regencies (Ngada, Ende, Sikka and Flores Timur) on Flores Island and two archipelagoes belonging to South Sulawesi and Southeast Sulawesi provinces. Figure 42 shows the number of swept away and completely collapsed houses, including both the damage due to the earthquake and that due to the tsunami. The total for the entire Flores Island is 16,967 houses. Most house damage in Ende and Ngada Regencies seem to have been caused by the earthquake, while that in Flores Timur was caused by the tsunami. Aggregating the amount of house damage, caused by the tsunami on both Sulawesi Provinces, we determined the total number of collapsed houses throughout Indonesia to be 17,697. But we should note the following fact: As mentioned above, the number of washed-away houses at Riang-Kroko and Bunga-Koten villages was about 200 and 100, respectively. Additionally house damage also was sustained at

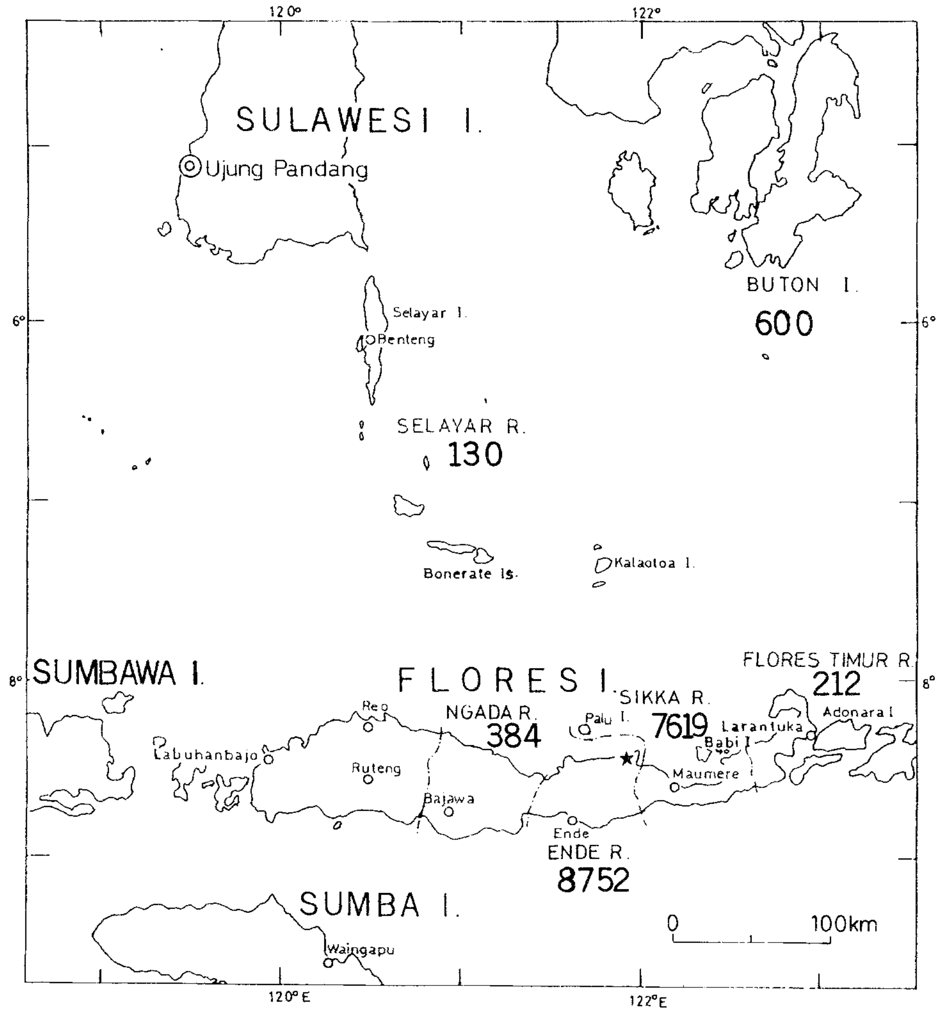

Figure 42
Number of houses totally destroyed (including washed away) by the earthquake and tsunami by regencies.

Pantai Lato, Pantai Lela, and other villages, therefore we must conclude that the damage statistics for the Flores Timur Regency (212) is substantially underestimated.

5.3 Number of Killed Persons

The number of deaths is given in Figure 43, which includes victims of both the earthquake and the tsunami. The total number of deaths on Flores Island is 1,690. Adding 22 deaths in South Sulawesi and Southeast Sulawesi Provinces, 1,702 people were killed in the entire Indonesian territory.

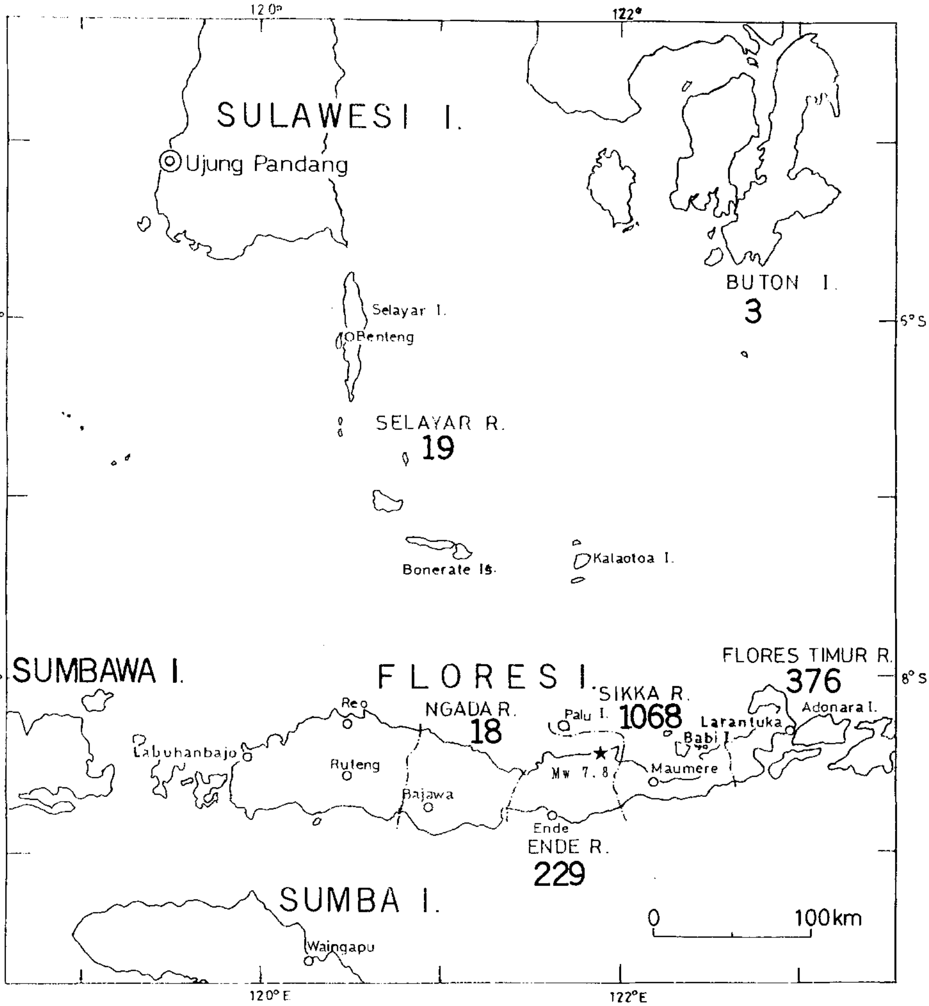

Figure 43
Number of deaths by regencies.

Comparing Figure 42, we can calculate the ratio of lives lost to the number of completely damaged houses for each regency. The ratios are 0.047 and 0.022 for Ngade and Ende regencies, respectively, where the damage was predominately caused by the earthquake. On the other hand, the ratios for Sikka and Flores Timur regencies are 0.145 and 1.774, respectively, where the damage was caused mainly by the tsunami. From this we can conclude that people were more swiftly killed by the tsunamis than by the earthquake.

5.4 Relationship between Tsunami Height and the Ratio of Mortality for Villages

We obtained information pertaining to the casualties suffered in coastal villages from articles in the newspaper, KOMPAS, and from other sources. We calculated mortalities, the ratio of victims to population, for seven villages on the damaged coast (circle graphs in Fig. 41). Approximately one fourth of the population was killed on Babi Island, and one third perished at Riang-Kroko village. In cases in which tsunami height exceeded 5 m some villages suffered mortality of several tens of percent. This fact also was recognized in the case of the MEIJI (1896) and SHOWA (1933) Sanriku tsunamis in Japan. If these people had had advance knowledge of the tsunamis, and had taken appropriate action upon feeling the earthquake, the mortality rate could have been substantially reduced.

6. Discussions and Conclusion

IMAMURA *et al.* (1995) demonstrated that it is difficult for fault models to fit the distribution of tsunami height even if two faults are assumed to occur separately in the eastern and western parts of the epicentral area, and if the amount of dislocation of the eastern plane is several times larger than that of the western. Historical data show that landslides sometimes generate tsunamis and/or increase the magnitude of the tsunami.

In Japan, examples of tsunamis induced by landslides are minimal. We know of only one example: the 1792 Ariake Bay Tsunami was induced by a large-scale landslide on the east slope of Mayuyama Hill, Shimabara Peninsula, Kyushu Island. For the Flores Island event, it appeared that landslides took place in the coastal region of Uepadung in Hading Bay. Extraordinarily high tsunami runup heights observed at Riang-Kroko village and its vicinity suggest that for the present event, landslides in the coastal and sea areas are partially the cause.

We examined the historical data for tsunami damage in Japan, for example, relative to the 1854 Ansei Tokai and Nankai Tsunamis, the 1896 and 1933 Great Sanriku Tsunamis, and others. We found that it is rare in the tsunami history of Japan that most houses were swept away by tsunami waves with heights of less than 5 m. Perhaps Indonesian carpenters can learn from the Japanese regarding the reinforcement of wooden houses against the horizontal forces, such that coastal houses of Indonesia would be safer from tsunamis. Specifically, wooden houses of Indonesia should use more diagonal bars.

At some coastal areas rocks fell along the slopes and sea water reached close to the foot of the slope of the hill behind the villages. In those cases, falling rocks may have prevented the inhabitants from evacuating safely. At Inaho village on Okushiri Island, Japan, falling rock also prevented the inhabitants from moving to higher ground at the time of the 1993 Hokkaido-Nansei-Oki Tsunami. In planning emergency shelters in the higher fields behind coastal villages, the possibility of rockfalls should be taken into account.

It is valid to protect coastal villages from the damage of tsunamis by planting trees in front of the residential areas. A zone of arranged trees, a greenbelt, cannot prevent sea water from flowing into the villages, but we can expect it to effectively dissipate the energy of the incident waves of the tsunamis, and to reduce the number of victims. For the Flores Island event, a row of palm trees had been planted in front of several villages, however it seemed that the row of trees was not very effective in dissipating tsunami energy. In most of these cases, the greenbelt was formed only by a line of palm trees. A palm tree generally has few low branches. If we want to improve the efficiency of dissipating the tsunami energy, then we should select varieties of trees that have many low branches with a high density of leaves.

We also noticed, in the case of Wuring and the villages of Babi Island, that a wide coral reef is an effective dissipation of tsunami energy. TSUJI and HINO (1993) noticed in the case of the 1792 Ariake tsunami, that tsunami height diminishes at a coast with a wide reef. This happens because the maximum height of a solitary wave is limited up to seventy percent of the depth, consequently if the wave height exceeds that limit, the wave energy will be lost by breaking at wave crests. It is worthwhile to consider the effect of a wide reef on the dissipation of tsunami energy when planning the locations of new coastal villages in tropical countries.

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Appendix 1

List of the measured tsunami heights of uncorrected and those of the tide (at measured time from mean sea level, MSL) corrected values. The standard port of the astronomical tide is Maumere. Six components of M2, S2, K1, O1, P1, and K2 are used for the tide calculation. The accuracy of heights of most of the points is estimated to be 0.1 m, except three points with marks "B" and "C" in the column of the reliability (R.B.), where B means slightly less reliable, and C means less reliable.

Location	GPS Measurement Lat. 8° S +	GPS Measurement Long. 122° E +	date	Measured time	height no correction	Astrn. Tide	Tsunami height above MSL	R.B.
1. from Maumere to west	′ ″	′ ″	y m d	h m	cm	cm	cm	
Maumere port 1	37 03.0	13 09.0	92 12 29	15:16	156	+48	204	
Maumere port-2			12 29	16:00	119	+65	184	
Wuring-1 (tip)	36 56.0	12 14.0	12 30	08:45	–			
Wuring-2			12 30	08:45	322	−56	266	
Wuring-3	36 00.0	12 12.0	12 30	08:45	354	−56	298	
Wuring-4	36 04.0	12 10.0	12 30	08:45	373	−56	317	
Wuring-5	36 04.0	12 10.0	12 30	10:25	269	−89	180	
Wuring-6			12 30	08:45	364	−56	308	
Wuring-7			12 30	08:45	414	−56	358	
Wuring-8	36 14.0	12 03.0	12 20	08:45	384	−56	328	
Wuring-9			12 30	08:45	390	−56	334	
Wuring-10			12 29	14:40	210	+30	240	
Wuring-11					280	+30	310	
Wuring-Mosque			12 29	15:06	276	+44	320	
(3 traces)					259	+44	303	
					248	+44	292	
(Average of Wuring)							(296)	
Wailiti-1	35 16.2	11 02.8	12 31	10:35	279	−71	208	
Wailiti-2	35 21.8	10 56.6	12 31	10:35	249	−71	178	
Nangahureh	34 18.3	10 14.3	12 30	15:38	140	+50	190	
Patisomba	33 01.8	8 38.5	12 30	16:10	335	+64	399	
Waturia	32 48.8	7 57.2	12 31	11:00	362	−74	288	
Nagarasong	32 24.8	7 14.9	12 31	14:54	473	+15	488	
Kolisia	32 33.5	5 17.5	12 31	15:50	470	+47	517	
Magepandang-Deteh 1	31 49.1	2 10.6	12 31	17:20	152	+78	230	
Magepandang-Deteh 2	31 50.7	2 13.2	12 31	17:20	146	+78	224	
Awora	29 36.2	121°51 08.5	93 1 2	14:10	311	−23	288	
Mausambi	30 34.1	121°47 10.1	1 2	12:50	379	−42	337	
2. Islands, north offshore								
Palu I. Mage 1			1 5	9:45	278	+6	284	
Palu I. Mage 2			1 5	9:57	244	+8	252	

Appendix 1 (Contd)

Location	GPS Measurement Lat. 8° S +	Long. 122° E +	date	Measured time	height no correction	Astrn. Tide	Tsunami height above MSL	R.B.
Pomana B.I. Ngolo-1			92 12 30	11:20	350	−82	268	B
Pomana B.I. Ngolo-2			12 30	11:20	400	−82	318	
Pomana B.I. Buton			12 30	13:05	194	−42	152	
Besar I. Taot	25 30.7	20 09.3	12 30	17:00	203	+76	279	
Besar I., Kusung Pandang	26 48.4	24 32.1	12 31	11:50	486	−72	414	
Parmahan I.	27 20.0	26 41.0	93 1 2	15:30	320	+16	336	
Babi I., Moslem V-1 (Kampungbaru)	26 6.0	30 21.0	1 2	13:15	395	−38	357	
Babi I., Moslem V-2	(V. western end)		1 4	12:24	723	−9	714	
Babi I., Moslem V-3	(40 m west of V.2)		1 4	12:35	725	−10	715	
Babi I., Chrst. V-D (Pagaraman)	25 45.7	30 50.0	1 4	12:20	570	−7	563	
Babi I., Chrst. V-E	25 44.8	30 48.4	1 4	12:20	549	−7	542	
Babi I., Chrst. V-F	25 42.2	30 50.3	1 4	12:20	464	−7	457	
Babi I., Chrst. V-G			1 4	12:20	415	−7	408	
Babi I., Chrst. V-H			1 4	12:20	407	−7	400	
(Average of Babi I. Chrst. V.)							(474)	
3. East of Maumere								
Permatasari Beach Hotel	37 39.3	14.10.9	92 12 29	12:20	238	−56	182	
Kampungburu	37 49.0	14 34.0	93 1 1	10:00	335	−37	298	
Waioti	38 14.0	16 20.0	1 1	10:40	295	−49	246	
Geliting	38 32.0	17 24.0	1 1	10:55	380	−53	327	
Kewapante	38 08.0	18 38.0	1 1	11:20	120	−56	64	
Egon	36 41.0	24 19.0	1 1	12:15	235	−57	178	
Wodung	35 00.0	29 31.0	1 1	14.05	255	−23	232	
Nangahale	33 19.0	30 38.0	1 1	14:35	160	−7	153	
Talibura Market	31 38.0	31 12.0	1 1	15:25	215	+22	237	
Daratgnung	30 00.3	28 49.8	(not recorded)		281	+49	330	
Nebe-West	27 44.8	30 33.2	(not recorded)		466	−18	448	
Nebe-1	27 57.0	32 04.0	1 3	13:25	417	−26	391	
Nebe-2	28 10.0	31 58.0	1 3	13:51	385	−23	362	
Nebe-3			1 3	14:15	433	−17	416	
Nebe-4 (V. center)	27 50.0	32 24.0	1 3	15:17	400	+3	403	
Nebe-5			1 3	15:17	357	+3	360	
Nebe-6			1 5	12:02	292	+10	302	
Nebe-7	27 50.1	32 17.9	1 5	12:25	453	+8	461	
Nebe-8	27 49.7	32 28.5	1 3	11:30	350	−18	332	
(Average of Nebe-1 to 8)							(378)	
Wailamung	25 29.4	35 22.0	1 5	12:20	538	+12	550	
Pantai Lato-1	21 11.3	46 10.0	1 1	14:54	345	+4	349	
Pantai Lato-2			1 1	15:02	340	+8	348	
Pantai Lato-3			1 1	15:15	360	+16	376	
Pantai Lato-4			1 1	16:10	310	+47	357	
Pantai Lato-5	21 20.0	46 05.5	1 1	15:32	325	+26	351	
Pantai Lato-6			1 1	16:47	297	+64	361	

Appendix 1 (Contd)

Location	GPS Measurement Lat. 8° S +	GPS Measurement Long. 122° E +	date			Measured time	height no correction	Astrn. Tide	Tsunami height above MSL	R.B.
Pantai Lato-7			93	1	1	17:10	277	+73	350	
(Average of P. Lato)									(356)	
Pantai Lato-North	21 30.9	45 57.1		1	1	16:35	630	+58	688	
Uepadung	17 42.6	49 56.8		1	3	11:50	1120	−22	1098	
Leworahang	17 23.1	52 39.2		1	2	12:50	14m*	–	14m*	C
Waibalan 1	16 51.9	53 13.3		1	2	13:30	622	−34	788	
Waibalan 2				1	2	13:40	1090	−32	1058	
Pantai Lela-1	11 21.9	50 08.6		1	3	10:47	347	−29	318	
Pantai Lela-2	11 08.2	50 14.7		1	2	11:06	483	−34	449	
Riang-Kroko 1				1	2	13:50	1865	−29	1836	
Riang-Kroko 2				1	2	13:50	1754	−29	1725	
Riang-Kroko 3	9 01.4	47 00.3		1	2	13:50	1778	−29	1749	
Riang-Kroko 4	9 01.9	47 00.8		1	3	12:45	2645	−27	2618	
(Average of R. Kroko)									(1982)	
Bunga-Koten (= Bou Tanabeten)	06 40.6	47 44.3		1	3	13:30	1250	−25	1225	
4. South Coast of Flores										
Larantuka, wharf	20 33.1	59 18.4		1	2	9:40	200	−25**	175	
Konga	26 36.5	47 04.8		1	1	13:03	90	−12**	78	C
Ende				1	5		50*	–	50*	

* Net height by eye measurement.
** The standard port of the astronomical tide for Konga and Larantuka is Lamakera on Solor Island.

Appendix 2

Statistics of human and building damage by regency. Reported by the Military Commander of Maumere on December 30, 1992. Number with parentheses are reported by Sikka and Ende Regency Offices on January 4, 1993, and December 22, 1992, respectively.

Regency	Population thousand	Deaths	Injured heavily	Injured slightly	Houses totally collapsed
Sikka	247	1,068	252	1,256	7,619
		(1,103)	(392)	(1,597)	(8,057)
Ende	219	229	228	336	8,752
		(193)	(228)	(333)	(8,752)
Ngada	198	18	9	11	384
East Flores	265	376	21	31	212
Total	929	1,691*	510	1,634	16,967**
		(1,690)	(650)	(1,972)	(17,405)

* In addition 3 people were killed due to the tsunami on Buton Island in Southeast Sulawesi Province and 19 people were killed in Selayar Regency, South Sulawesi Province.
** In addition 130 and 600 houses were swept away on Kalaotoa Island, South Sulawesi Province and on Buton Island in Southeast Sulawesi Province, respectively.