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TSUNAMI OF THE SUMBA EARTHQUAKE OF AUGUST 19, 1977

Kenji KATO
East Japan Railway Company, Dormitory of JR East Co.,
Kozai 1-1-5, Niigata City, 950, Japan
and
Yoshinobu TSUJI
Earthquake Research Institute, University of Tokyo,
Yayoi 1-1-1, Bunkyo-Ku, Tokyo, 113, Japan

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ABSTRACT

A large earthquake of normal type with a magnitude (M_w) of 8.3 occurred off the southwest coast of Sumba Island, Indonesia at 14h 08m local time (06h 08m GMT) on August 19, 1977. It caused a large tsunami which struck the south coasts of Bali, Lombok, Sumbawa, and Sumba Islands. Tsunami heights were 5–8 meters at Lunyuk on Sumbawa Island, and 5 meters at Leterua on the south coast of Sumba Island. Hatori's tsunami magnitude was estimated as $m=3.5$ from data on the tsunami heights at 15 points on the Indonesian and Australian coasts. Numbers of casualties and missing persons respectively were 107, and 54, and most were victims of the tsunami. We made a numerical calculation of tsunami propagation by assuming two sets of fault parameters. The simulation showed that the tsunami height distribution was well reproduced numerically for the larger dislocation in the western part of the fault plane than in the eastern part. After the main shock, loud noises that sounded like explosions were heard three times at several points northwest of the epicenter. Similar noises were heard during the 1933 Great Sanriku Earthquake-Tsunami, also a normal type event. We speculate that such noises are peculiar to normal type earthquakes.

1. INTRODUCTION

A large earthquake with magnitude Mw 8.3 occurred off the southeast coast of Sumba Island, Indonesia, at 6h 08m GMT (14h 08m local time) on August 19, 1977 (Given and Kanamori 1980). The epicenter was at 11.08°S, 118.46°E (by NEIC, USGS) in the north sea region of the axis of the Java Trench, where the Indian-Australian Plate sinks down northward below the Lesser Sunda Islands (Spence, 1986, Lynnes and Lay, 1988).

The earthquake had the same characteristics as the Great Sanriku Earthquake of 1933, which was a normal fault type event caused by breakage in the sinking plate (Kanamori, 1971). The earthquake caused a large tsunami which struck the south coasts of Bali, Lombok, Sumbawa, and Sumba Islands. It also struck the north coast of Australia. Journalists reported tsunami heights of 10 to 15 meters on the south coast of Sumbawa Island and of about 6 meters on the north coast of Australia.

Soloviev et al.(1986) reported that marked withdrawal of the sea was observed by eyewitnesses before arrival of the first crest of the wave. Three waves came at intervals of 5 minutes or less, the first being the largest. The inhabitants of Lombok and Sumbawa Islands three times heard noises like a bomb exploding. The sea water temperature rose after the tsunami. The tsunami also struck the north coast of Australia. At Dampire the wave reached a height of 2 meters, at Port

KEY WORDS: 1977 Sumba earthquake, Normal type earthquake, Damage of tsunami, Earthquake and tsunami magnitudes.

Sampson the height varied from 2 to 4 meters, and at Cape Levek it was 6 meters.

Just after the event, a field survey was made by a joint team organized by officers of the Meteorological and Geophysical Agency of Indonesia (MGA) and scientists of the International Tsunami Information Center (ITIC), Honolulu, Hawaii. The results of this survey were summarized in two reports: one written in the Indonesian language by the MGA(1977), the other written in English by the ITIC (1977). Tsunami run-up heights above sea level at measured times were given for 12 villages. It also was reported that more than 100 people were killed, 89 lost, and 75 injured. Tsunami waves several centimeters high were recorded at three far tide gauges on the Australian coast; at Service Wharf, at Tug Jetty, and at Legendre Island (Soloviev et al., 1986). No tide record was obtained on the Indonesian coast.

We visited several villages on the south coasts of Bali and Lombok Islands, and gathered eyewitnesses' accounts over a few days in October 1993. Officers of the meteorological observatories at Denpasar (Bali Is.) and Mataram (Lombok Is.) guided us to the struck villages and helped us to communicate with the inhabitants.

We here reviewed those accounts and mention the result of our field survey. We estimated the tsunami magnitude, discuss the explosive noises heard and the human damage suffered, and made numerical calculations of tsunami propagation.

2. EYEWITNESSES' ACCOUNTS OF THE TSUNAMI OF THE 1977 SUMBA EARTHQUAKE

2.1 Damage to villages on the south coasts of the Lesser Sunda Islands

On the basis of the two published reports, we review the striking of tsunami waves at 13

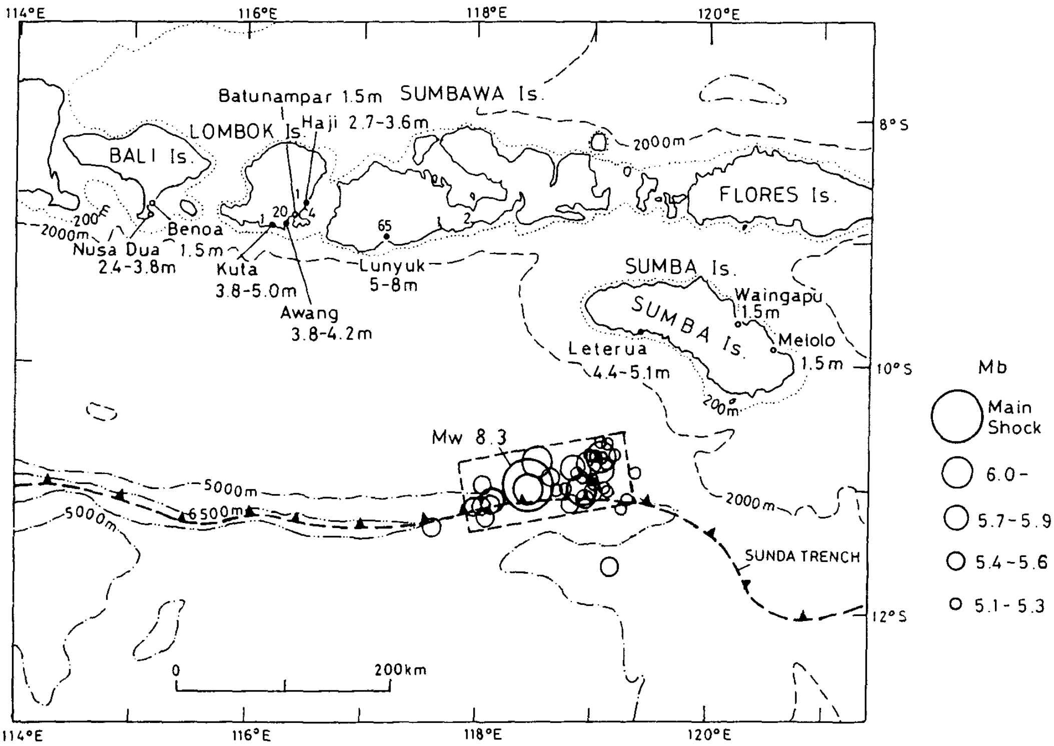

Fig. 1. Locations of the main shock and aftershocks of the Sumba Earthquake (Mw 8.3) of August 19, 1977. Tsunami height ranged at 10 villages on the coasts of Lesser Sunda Islands also are shown. Astronomical tide components at the time of the surveys have been deleted. Numbers on the coasts are the number of casualties. Black circles denote villages where the initial withdrawal of the sea was reported.

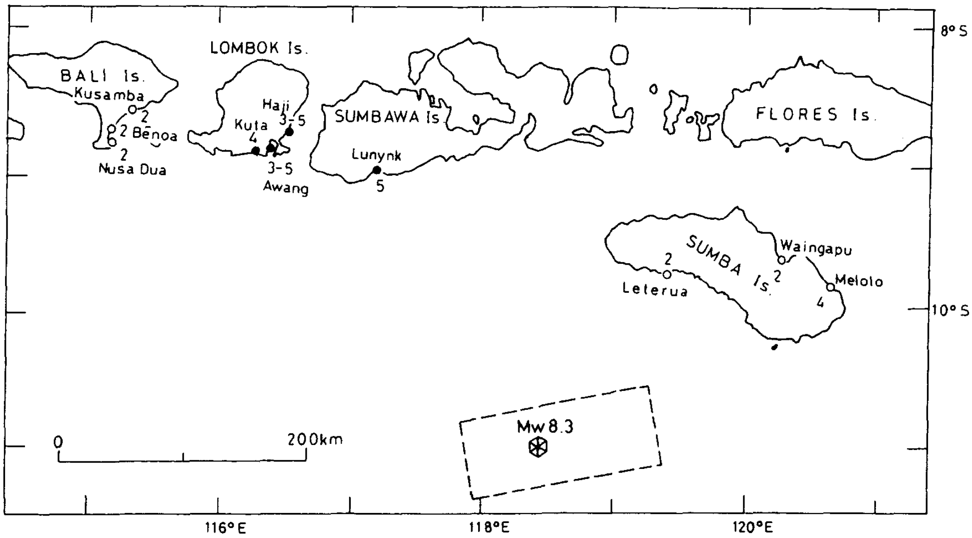

Fig. 2. Duration (unit, minutes) of strong shaking of the main shock. Black circles denote villages where explosive noises were heard for three times in succession. Hexagon: the location of the epicenter of the main shock. Rectangle: the location of the fault plane.

villages on the south coasts of the Lesser Sunda Islands; from Bali to Sumba Island. The measured tsunami heights were given in the published reports. Eyewitnesses' accounts gathered during our field survey of several villages on Bali and Lombok Islands, are discussed. The locations of these villages are shown in Figs. 1 and 2.

(a) Nusa Dua (Bali Island, 8°48'S, 115°13'E)

Nusa Dua Town is located on the east coast of the Bukit Badung Peninsula in the southern part of Bali Island. Nusa Dua Bay faces east to the open ocean. Strong horizontal shaking was felt for several minutes. Tsunami heights measured at two points were 2.5 and 4.0 meters above sea level. Waves came three times. The sea water did not reach the edge of the sandy shoreline, nor did it invade the residential area. No damage was caused by the tsunami waves.

(b) Benoa (Bali Island, 8°46'S, 115°13'E)

Benoa, on the east coast of Bali Island, is the outer port of Denpasar City. Its harbor area measures 4 kilometers east-west and 6 kilometers north-south, and the width of the harbor mouth is one kilometer. There is a depth of at least 5 meters in the harbor area at ebb tide. Strong horizontal shaking was felt for several minutes. The height of the tsunami was 1.5 meters. No damage occurred.

(c) Kusamba (Bali Island, 8°35'S, 115°23'E)

Kusamba Village is located in the southeast of Bali Island and faces southeast to the open ocean. An island named Nusa Penida lies to the southeast off this coast. Strong horizontal shaking was felt for several minutes, but no evidence of a tsunami was observed.

(d) Haji (Lombok Island, 8°43'S, 116°33'E)

Haji Village is located on the east coast of Lombok Island. Strong shaking was felt for 3 to 5 minutes, and the walls of some houses collapsed. Noises that sounded like bombs exploding were heard three times over 10 minutes after the shaking by the main shock ended. The first wave arrived at the village 8 minutes after these noises. The sea water first withdrew, then rose up and flooded over the boundary of the sandy shore. The sea water reached 3.2 meters above the mean sea level. Waves came from the south, and broke at their crests forming white caps on the sea surface in the harbor area. The sea surface appeared black due to the disturbance of bottom sediments.

Sea water inundated a palm tree grove 100 meters from the shoreline 2 kilometers north of the village. The inundation height was 4.1 meters. The tsunami height was 3.8 meters 1 kilometer south of the village. Fishing boats were wrecked, but no one was killed.

(e) Awang (Lombok Island, 8°55'S, 116°24'W)

Awang Village is on the west coast of Lombok Bay in the southern part of Lombok Island. The depth of the bay is several tens of meters. The residential area is close to the coastline. Strong horizontal shaking was felt for 3 to 5 minutes. Noises like bomb explosions were heard three times. The inundation height of the tsunami was about 4 meters.

The sea first rapidly regressed 200 meters, then waves came at intervals of 3 to 5 minutes. The sea water reached a level of 2 meters above the top of the sand beach, and its temperature rose. The color of the surface water became brown. The waves were broken and foamed at their crests. Trees fell down or were uprooted. Houses near the coast were destroyed, and boats wrecked. The front column of the mosque in the village was broken but not carried away by the sea water. Traces of inundation clearly appeared on the walls of the mosque, the height of the tsunami there being 4.3 meters above the mean sea level. Inundation continued inland for about 200 meters from the shore.

(f) Batunampar (Lombok Island, 8°51'S, 116°25'E)

Batunampar Village is located on the innermost coast of Lombok Bay. There is a shoal in front of the shoreline, which protected the coast from the striking waves. The earthquake was felt strongly. Sea water reached a level only 0.6 meter higher than the level at the flood of the astronomical tide, 2.0 meters above the mean sea level. The temperature of the sea water rose.

(g) Kuta (Lombok Island, 8°53'S, 116°12'E)

Kuta Village is in the center of the southern coast of Lombok Island. The residential area is only several tens of meters from the sandy shore. Shaking was felt for four minutes and after a while, noises like thunder were heard three times. Five minutes after these noises, the sea water withdrew 300 meters, and the surface water became black. The sea water was one meter above the highest point of the sandy shore and inundated the land for 100 meters. One person was killed, and boats were wrecked. The first wave was the biggest, and waves continued to hit the coast at intervals of 5 to 10 minutes. The run-up height was measured as 4.3 meters in the residential area of the village. A tsunami height of 5.5 meters was measured at a point south of the village, where the coast is open to the ocean.

(h) Ampenan (Lombok Island, 8°33'S, 116°04'E)

Ampenan City is located on the west coast of Lombok Island. Strong shaking was felt. No evidence of tsunami was observed.

(i) Jereweh (Sumbawa Island, 8°50'S, 116°48'E)

Jereweh Village is on the coast facing the Alas Straits between Lombok and Sumbawa Island. Thirteen people were killed by the tsunami. No information was reported on tsunami height.

(j) Lunyuk (Sumbawa Island, 9°02S, 117°10'E)

Lunyuk Village is located at the mouth of the Beh River in southern Sumbawa Island. The inundation height of the tsunami was estimated by eye as 5–8 meters. Shaking was strong for 5 minutes. Noises like bomb explosions were heard three times. The sea withdrew 400 meters at first, then rose and inundated the land 500 meters beyond the shoreline. Sixty five persons were killed.

(k) Leterua (Sumba Island, 9°46'S, 119°12' E)

Leterua Village is on the west coast of Sumba Island. The coast is open to the south and has coral spits. Shaking was felt for several minutes, but no noise was heard. The initial wave came five minutes after the main shock from the southeast. The tsunami height was 5.5 meters at a point near the residential area, 4.8 meters at a palm tree grove near the river mouth 800 meters southwest of the village, and 5.5 meters at the inundation limit 1200 meters from the shoreline.

(l) Melolo (Sumba Island, 9°56'S, 120°45'E)

Melolo Village is located on the east coast of Sumba Island, facing the ocean. Strong horizontal shaking in the NE-SW direction was felt for four minutes. No noise was heard there. Few buildings were damaged. Because the astronomical tide phase was eventually near the ebb, little human damage occurred. The inundation height was only 1.5 meters.

(m) Waingapu (Sumba Island, 9°38'S, 120°16'E)

Waingapu City is located on the northeast coast of Sumba Island. Shaking was felt strongly for several minutes. No noise was heard. Waves came at intervals of 4 to 6 minutes. The wave height was 3 meters. The sea surface was abnormal until 18h30m (local time), about 4 hours after the main shock. No damage occurred in the port.

2–2. Summary of seismic descriptions

There are a few descriptions of the earthquake damage suffered in this event. Walls fell down at Haji on Lombok Island, but little damage to buildings due to the earthquake was reported. The damage done was caused mainly by the tsunami triggered by this earthquake.

The distribution of the durations of strong shaking is shown in Fig. 2. The duration of shaking was relatively long on Lombok and Sumbawa Islands, but short on Bali and Sumba Islands. The duration was short on Bali Island even though Bali is far from the epicenter.

2–3. Tsunami heights

The component of the astronomical tide at the time measured should be subtracted from the measured tsunami heights. We prepared an astronomical tide table using the coefficients of astronomical tide at Bali, Lombok, and Sumba Islands, which were provided by the Japan Oceanographic Information Center (JOIC) of the Marine Safety Agency of Japan. Tsunami heights were highest on the south coast of Sumbawa Island and the west coast of Sumba Island and were smallest on the coasts of Lombok and Bali Islands (Table 1, and Fig. 1). Tsunami height attenuation for epicentral distance west of the source is clear. But poor information was given for east of Sumba Island. Black circles in Fig. 1 show the points where the initial motion of the tsunami was withdrawal. For most of the damaged coasts the first sea level change reported was a downward motion, indicative that the crustal motion in the north part of the source area was subsidence. In earthquakes of the normal type, a prominent subsidence area generally is formed in the land side part of the source area, and the initial tsunami comes as a wave with downward motion. In the 1933 Great Sanriku Earthquake-Tsunami, the initial drop in the sea level occurred 30 minutes after the main shock on the coast nearest the source. In the Kikai Island Earthquake Tsunami of October 18, 1995, marked withdrawal of sea water was reported by the inhabitants' eyewitness accounts in several villages 5 to 10 minutes after the main shock, which was also a normal type shock (Kikuchi, 1995).

3. TSUNAMI MAGNITUDE

The definition of tsunami magnitude, m on the Imamura-Iida scale was extended by Hatori(1986), who proposed a method of estimating the tsunami magnitude from the averaged inundation heights H (unit; meter) and the epicentral distances D (km). He obtained the empirical formula

$$m = 2.7 \log H + 2.7 \log D - C \tag{1}$$

where C is a constant and assigned a value of 4.8 for large tsunami with magnitudes of more than $m = 1.5$. In Figure 3, the inundation height is plotted against the epicentral distance for each

Table 1. Measurement of tsunami heights

Island	Place Name	Location Lat. S	Location Long. E	Height Measured	Height Above MSL
Bali	Nusa Dua	8°48'	115°13'	2.5, 4.0m	2.3, 3.8m
	Kusamba	8 35	115 23	-	-
	Benoa	8 46	115 13	about 1.5	about 1.5
Lombok	Haji	8 43	116 33	3.2,4.1, 3.8,4.0	2.7,3.6, 3.3,3.5
	Awang	8 55	116 24	4.3,4.0	3.8,4.2
	Batunampar	8 51	116 25	2.0	1.5
	Kuta	8 53	116 12	4.3,5.5,5.0	3.8,5.0,4.7
	Ampenan	8 33	116 04	-	-
Sumbawa	Jereweh	8 50	116 48	-	-
	Lunyuk	9 02	117 10	about 5–8m	-
Sumba	Leterua	9 46	119 12	4.8, 5.5 5.0	4.4, 5.1 4.6
	Melolo	9 56	120 45	about 1.5	about 1.5
	Waingapu	9 38	120 16	about 1.5	about 1.5
Australia	Cape Levek	16°24	122°55	Double Amp.	about 6m
	Port Sampson	20 38	117 12	Double Amp.	2–4m
	Dampire	20 40	116 42	Double Amp.	2.0m

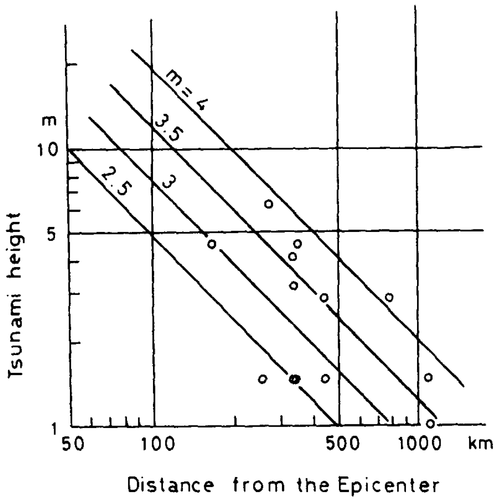

Fig. 3. Attenuation of tsunami heights with epicentral distance for different tsunami magnitudes given by the formula (1), Open circles show tsunami height above the mean sea level for the Sumba earthquake.

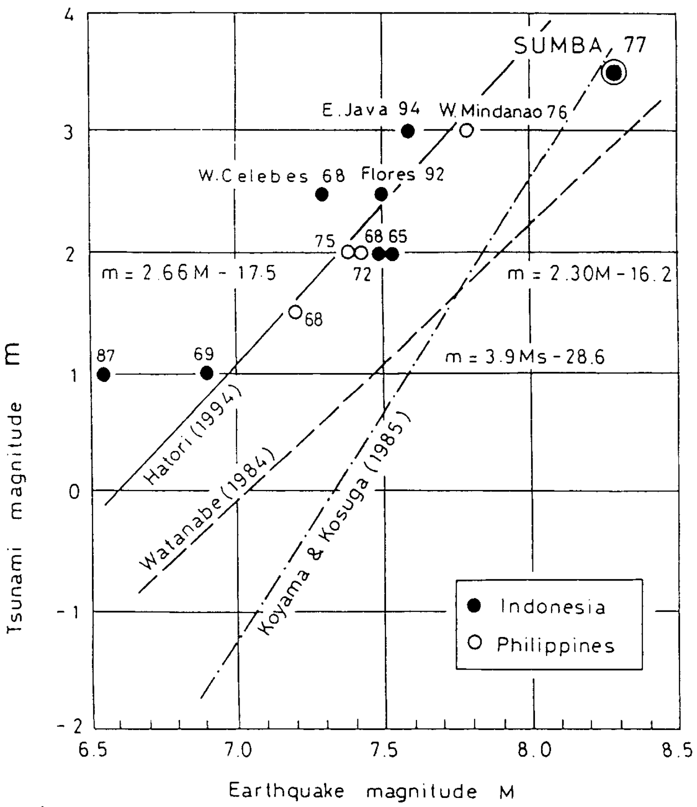

Fig. 4. Relationship between the earthquake and tsunami magnitudes. Solid line: the regression line for the Indonesia-Philippine region (Hatori, 1994). Dashed line: the regression line for the Japanese Islands (Watanabe, 1984). Chain line: the regression line for 16 of the largest earthquakes in the world (Koyama and Kosuga, 1985).

reported point (white circle). One circle representing the averaged height is given for each village. For the data on Australian coasts reported in Soloviev et. al (1986), we regarded the 'height' as the double amplitude of a wave and estimated the net tsunami height as half that value. We did not plot the tsunami height of 10 to 15 meters given by journalists because it lacks reliability. Solid lines show the tsunami magnitude defined by formula (1) when $C=4.8$. The tsunami magnitude, m, for the Sumba event is estimated as $m=3.5$.

Watanabe (1984) obtained a relationship between earthquake (M) and tsunami (m) magnitudes using Japanese tsunami data for the modern period;

$$m=2.30\,M-16.2 \tag{2}$$

which is shown by the dashed line in Fig. 4. Koyama and Kosuga (1985) also proposed an empirical formula based on information on the world's largest events in addition to the Japanese data;

$$m=3.9\,M_s-28.6 \tag{3}$$

which is shown by the chain line in Fig. 4.

Hatori (1994) pointed out that the magnitudes of tsunami in the Indonesia-Philippine region are one to two grades higher than those generated by an earthquake of the same magnitude in another regions. He gave the regression formula for this region as

$$m=2.66M-17.5 \qquad (4),$$

which is shown by the solid line in Fig. 4. The circle plotted for the Sumba event is located between the dashed and solid lines close to the chain line; i.e. tsunami magnitude is smaller for the earthquake magnitudes in the Indonesia-Philippine region, but is the standard size of the world average for an earthquake magnitude of $M_w = 8.3$.

4. NOISES ACCOMPANYING THE EARTHQUAKE

There are several places where explosive noises were heard three times on Lombok and Sumbawa Islands, northwest of the source, between the occurrence of the main shock and the arrival of the tsunami. It is noteworthy that these noises without exception were heard three times at these places. At Haji on Lombok Island, the noises were heard continuously 10 minutes after the shaking of the main shock. As the shaking of the main shock was felt for 3 to 5 minutes, the noises came 13 to 15 minutes after the beginning of the shaking there. The epicentral distance for Haji is about 300 kilometers. The respective speeds of the P-wave in the crust and sound wave in the atmosphere are 8.0km/sec and 0.34 km/sec. The respective traveling times of P- and sound waves therefore are estimated as 37.5 seconds and 14.7 minutes. If the explosive noises were generated at the epicenter at the time of the main shock, their expected arrival time at Haji was 14.1 minutes after the arrival of the P-wave, which is consistent with the witnesses' account. Therefore the first explosive noise heard at Haji is judged to be the sound generated at the epicenter at the time of the main shock. These noises suggest the sound generated by the breaking of the Australian Plate. As explosive noises were heard three times, the plate appears to have broken three times in succession.

Inouye (1934) reported that, at the time of the 1933 Great Sanriku Earthquake, noises like the roaring of a cannon were heard at many places in the Tohoku district in the northeast part of the Honshu Island. Moreover, he suggested that these noises were not generated by tsunami but by the occurrence of the main and after shocks. As stated earlier, the 1993 Sanriku Earthquake and 1977 Sumba earthquake were of the same type, normal fault earthquakes caused by the breaking of plates. We conclude that such noises are peculiar to normal type earthquakes.

5. DAMAGE CAUSED BY THE TSUNAMI

The damage caused by the tsunami of the 1977 Sumba Earthquake was reported by the Meteorological and Geophysical Agency Indonesia (1977). Table 2 gives the damage done on Lombok and Sumbawa Islands. The heaviest damage took place at Lunyuk (Sumbawa Island), where 65 people were killed, 37 reported missing, 63 houses destroyed, and 10 boats wrecked. At Awang (Lombok Island) 20 people were killed, 115 houses destroyed, and 132 boats wrecked. The respective total numbers of killed and missing were 107 and 54.

There was no description of human or building damage on Sumba Island in any of the reports.

6. NUMERICAL CALCULATION OF THE TSUNAMI OF THE 1977 SUMBA EARTHQUAKE

The locations of 45 aftershocks ($M_b > 5.1$) that occurred for 7 days after the main shock are shown in Fig. 1 (Spence, 1986). We assumed that the fault plane was rectangular, its upper side parallel to the sea bed, and that the amount of dislocation and the rake direction were uniform on the plane. We estimated the length of the fault as 150 kilometers and the width as 70 kilometers.

The fault mechanism given by Harvard University is shown in Fig. 5. Two nodal lines are presented; one northward down at a low angle, the other southward down at a high angle. Assuming that the Sumba event was the same type as the 1933 Great Sanriku Earthquake, we regarded the former nodal line as corresponding to the dislocated fault plane. The respective values for the strike, dip, and rake angles therefore were 260°, 20°, and −73°.

The resolved stress moment was estimated as $2.4-4.0 \times 10^{21}$ Nm (Given and Kanamori, 1980), and the rigidity of the crust as 4.0×10^{10} N/m , so we assumed the amount of dislocation to be

Table 2. Damage statistics

Place Name	Human deads	Human missing	Human injured	Property damaged houses	Property ships
Lombok Is.					
Awang	20	-	499	115	132
Kuta	1	-	-	5	26
Gerupuk	4	-	-	-	13
Selong Belanak	-	-	-	-	19
Haji	1	-	-	-	96
Sumbawa Is.					
Lunyuk	65	37	339	63	10
Tatar Jereweh	-	12	60	-	-
Teonang Jereweh	-	12	60	-	-
Molule Jereweh	-	-	15	3	-
Empang	2	-	10	47	-
Plampan	1	3	20	-	-
Ropang	-	2	10	-	-
Total	107	54	1123	440	467

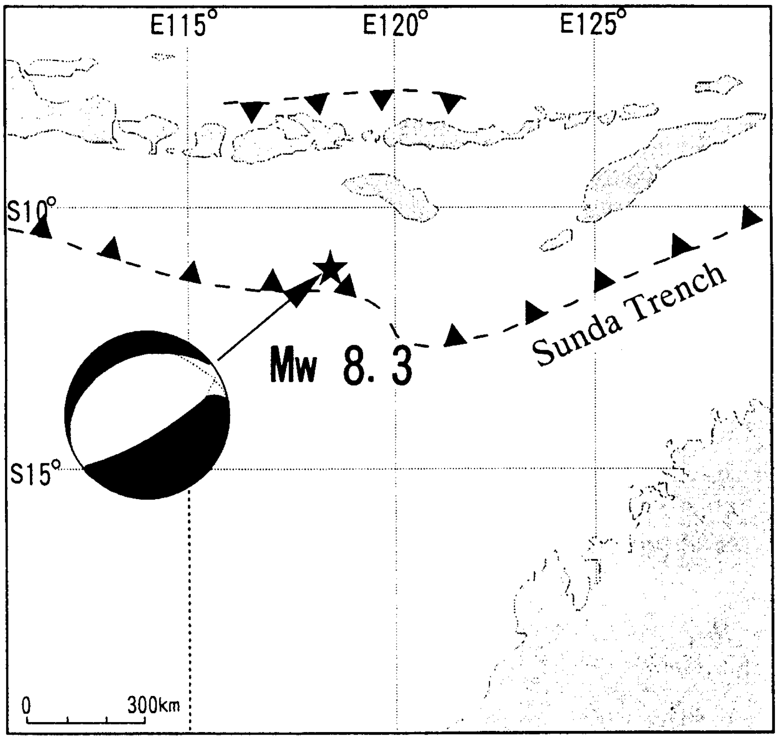

Fig. 5. Fault mechanism given by Harvard University.

7.0 meters (Table 3).

Table 3. Assumed fault parameters

strike	260°
dip angle	24°
rake	−73°
dislocation	7.0 m
width	70 km
length	150 km
depth	15 km
moment resolved	2.9 × 10^{21} Nm

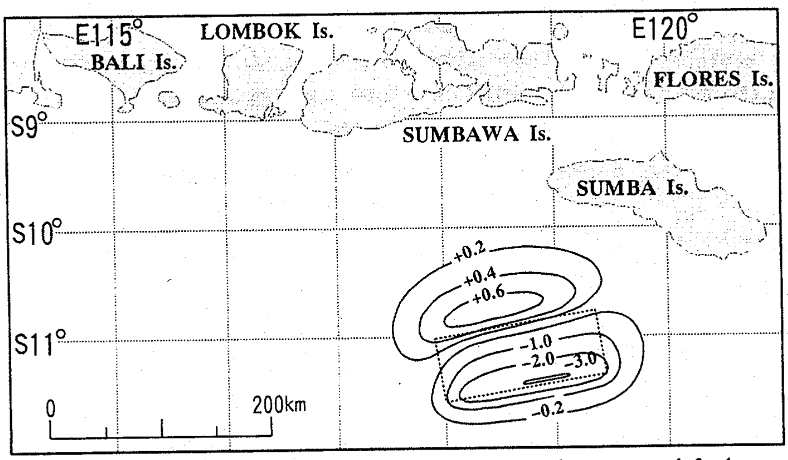

Fig. 6. Distribution of sea bottom deformation according to the assumed fault model (Table 3).

We assume that the sea surface displacement occurred at the moment of crustal motion and had the same shape of uplift and subsidence as the sea bed (Fig. 6).

A large subsidence area appears above the fault plane, and the maximum subsidence of the sea bed is 3.0 meters. An area of slight uplift (maximum 60cm) is seen in the north of the subsidence area.

We used a numerical grid mesh covering the area 8° to 12° S and 114° to 121°E, with a mesh size of 1.25 minutes (about 2.3 kilometers) in both directions. The 5' (about 9km) grid elevation file of the earth's surface compiled by NOAA, and sea charts published by the Hydrography Department of the Marine Safety Agency, Japan (Charts No. 1903, 1904, and 2860) were used. We neglected the terms for the molecular and eddy viscosities, dispersions, sea bottom friction, non-linearity, and rotation of the earth. The time step, ΔT selected was 3.0 seconds taking into account the stability condition (CFL condition);

$$\Delta T \leqq \frac{dx,dy}{\sqrt{2gh_{max}}} \tag{5}$$

where h_{max}, dx, dy respectively are the maximum depth, and grid intervals in x (eastward plus), and y (northward plus) directions.

We used a uniform depth for the continental shelf region of 200 meters instead of the actual values. We assumed that the waves were perfectly reflected at the coastal lines. Therefore, the amplification effect in the shallow zone will not be obtained with this scheme.

We roughly estimated the amplification factor in the tsunami run-up problem for the Sumba event. Shuto (1972) proposed a formula for run-up height in a one-dimensional case on the assumption that the inclination of the sea bed in the shelf region is a constant, the inclination of the land is the same as that of the sea bed, and the incident wave is a simple sinusoidal. He gave the formula for the amplification factor p as,

$$p=\sqrt{J_0^2\left(\frac{4\pi L}{\sqrt{gD}T}\right)+J_1^2\left(\frac{4\pi L}{\sqrt{gD}T}\right)} \tag{6}$$

where L, T, and D are the length of the shelf, the period of the incident wave, and the sea depth at the edge of the shelf (generally 200 meters). J_0 and J_1 are Bessel functions of the zero-th and the first order. For the Sumba event, $L=5-10$ km and $D=200$ meters. The period of the incident wave is roughly estimated from the calculations as 5–10 minutes (See Fig. 9). Placing these values in (6) we obtain the amplification factor $p=2.1$ to 4.0. Accordingly, we can give a rough value of 3 for the amplification factor; i.e., the realistic tsunami run-up height will be roughly threefold the numerical values calculated using our scheme.

7. NUMERICAL CALCULATION RESULTS

The distribution of the calculated tsunami heights on the south coasts of Bali, Lombok,

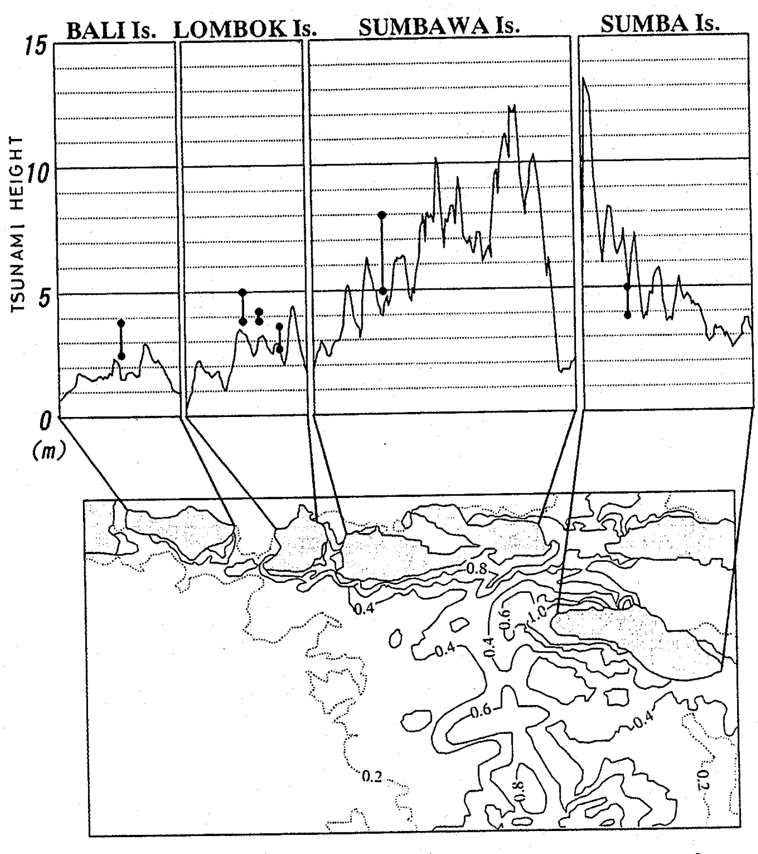

Fig. 7. Distribution of the calculated tsunami heights (curves in the upper figures) along the south coasts of Bali, Lombok, Sumbawa, and Sumba Islands. Effects of the amplification of wave height in the shallow sea region close to the coast are not taken into account, therefore, values three times the calculated heights are shown. Thick lines: the east and west limits of displayed coasts. Black circles: actual measured tsunami heights above the mean sea level.

Sumbawa, and Sumba Islands are shown by the solid lines in Fig. 7. The reported tsunami heights are shown by black circles connected by thick bars. Values that are threefold of the calculated tsunami heights are shown in the upper part of the figure because the amplification effect on the continental shelf region is not contained in the direct results of the numerical calculation. The contour lines are iso-lines for the maximum value of the calculated tsunami height.

Prominent peaks appear at the west end of Sumba Island and the east part of Sumbawa Island in the tsunami height distribution (Fig. 7). Those peaks formed as a result of the lens effect of the spur at the west tip of Sumba Island. Regrettably, neither the reports of the MGA (1977) nor the ITIC (1977) give the tsunami heights at those coasts where there are tsunami peaks. We note that the tsunami heights on the coasts of Bali and Lombok are relatively small, which does not agree with the actual reported tsunami height distribution.

To lessen the discrepancy between the numerical results and the reported tsunami heights, we assume that the dislocation on the western half of the fault plane is threefold that on the eastern half and again made another numerical calculation (see the next section).

8. NUMERICAL CALCULATION FOR THE REVISED FAULT MODEL

We improved the fault model by changing the dislocation distribution. We assumed the amount of dislocation on the western half of the fault plane to be 50 per cent larger and that on the eastern half 50 per cent less than in the original model. We did not change the fault length, width, dip, strike, rake directions, or the depth of the upper side.

Results of the numerical calculation for the revised fault model are shown in Fig. 8 which

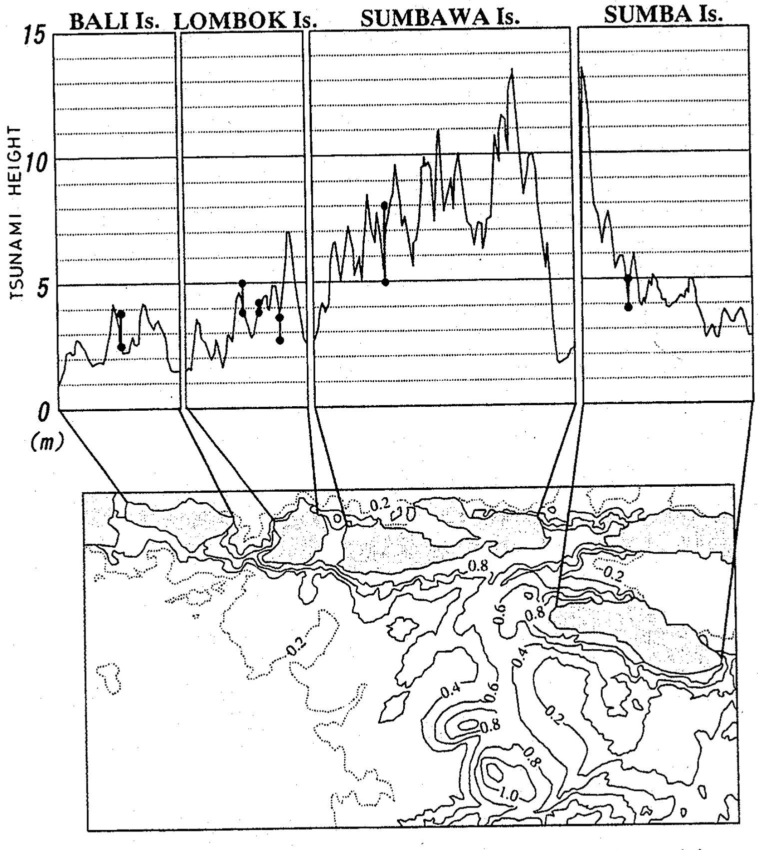

Fig. 8. The same as Fig. 7, but for the revised fault model.

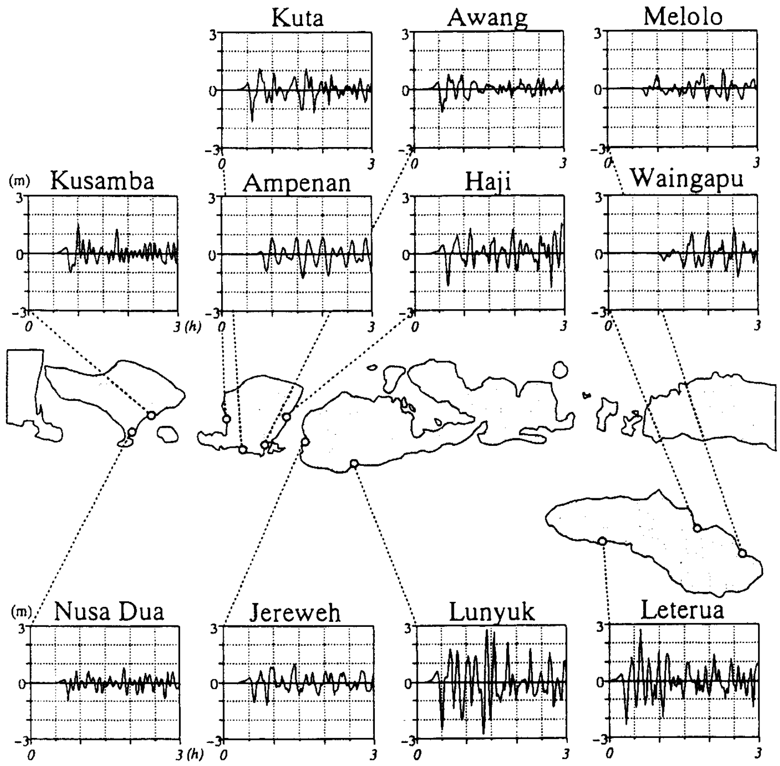

Fig. 9. Calculated sea level changes at 11 villages on the south coasts of the Lesser Sunda Islands up to three hours after the main shock. The original model was used.

gives the maximum height distribution of sea surface displacement. A comparison with Fig. 7 shows that there is only a slight difference in the tsunami height at Sumba Island, whereas tsunami heights on the coasts of Bali, Lombok, and Sumbawa Islands are larger than those provided by the original model.

9. NUMERICALLY CALCULATED SEA LEVEL CHANGES

We evaluated sea level change at eleven stations on the south coasts of Bali, Lombok, Sumbawa, and Sumba Islands. In addition to the original model with the simple grid, we set four grades of finer meshes near each reported point, and the sea level changes were obtained. The grid size of the finest mesh was 144 meters. The sea level changes at the eleven stations obtained with the revised model are shown in Fig. 9. The sea level change begins with a small crest followed by a large withdrawal that is prominent at all the stations but two on the northeast coast of Sumba Island. This large withdrawal appears to correspond to eyewitnesses' accounts at several places that stated that the sea water first withdrew.

10. DISCUSSION AND SUMMARY

We reviewed two reports on the 1977 Sumba Earthquake Tsunami; one by the Meteorological and Geophysical Agency, Indonesia, the other by the ITIC. The damage done mainly was due to tsunami, only slight damage being caused by the earthquake itself. Successive explosive noises were heard three times at several places on Lombok and Sumbawa Islands, whereas on Sumba Island, no such noises were reported even though the source distances are smaller than those for Lombok and Sumbawa Islands. Taking into account the arrival times of the noises, the sounds were generated at the epicenter at the time of the main shock. There is a directivity in the propagation of these noises from the Sumba earthquake; the noises propagated only northwestward, not northeastward. Silimar noises were reported at the time of the 1933 Great Sanriku Earthquake which had the same characteristics as the Sumba event;being a normal type earthquake caused by the breaking of the sinking plate. Probably such explosive noises are peculiar to earthquakes of normal type caused by the breaking of a sinking plate.

The initial motion of the tsunami was described as being the marked withdrawal of sea water at many of reported places. Tsunami eventually struck the coasts at the ebb of the astronomical tide; therefore, at some places the sea water fortunately did not flood above the edge of the sandy shore. The damage done in the Sumba event is considered not to be severe for the tsunami magnitude because of the lucky astronomical tide condition.

We made a numerical reproduction of the tsunami that was based on solutions for the mechanism and distribution of the aftershocks. We compared the numerically calculated tsunami heights with the reported ones. When the dislocation on the western half of the fault plane was assumed to be larger than that on the eastern half, we obtained a tsunami height distribution that better fitted the reported distribution than did that obtained by the uniform dislocation model.

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