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THE 1990 BOHOL EARTHQUAKE: TSUNAMI OBSERVATIONS AND EFFECTS AT BOHOL ISLAND, PHILIPPINES

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ABSTRACT

The earthquake of February 8, 1990 offshore the Island of Bohol in the Central Philippines was a tsunamigenic event caused by crustal displacements along an unknown northeast-southwest trending fault. Isoseismal distribution confirmed such orientation with higher seismic intensities at the southeastern areas of Bohol Island. Subsequent field surveys, interviews with eyewitnesses and measurements of runup heights, support that significant tsunami inundation occurred along the southeastern coast of the island. Based on this investigation and review of historical data, we conclude that the source region of the 1990 tsunami was along an unknown offshore submarine structure.

Keywords: seismic intensity, Alicia Thrust Fault, East Bohol fault, tsunami, runup, tsunami height, Bohol, Philippines, tsunami hazards

INTRODUCTION

The Bohol earthquake of February 8, 1990, had a magnitude M6.0 and occurred at 15:15:35.9 local time (PHIVOLCS, 1990). It was one of the strongest earthquakes to impact the island of Bohol in Central Philippines since the early 1900's. Though moderate in magnitude compared to the known devastating earthquakes in the Philippine archipelago, the 1990 Bohol earthquake nonetheless wrought havoc to at least 16 municipalities on the island - leaving behind numerous casualties, about three hundred injured, several thousand homeless and evacuated from coastal areas. Economic damage to properties was at least Php154 million. A detailed documentation of damages was undertaken by Umbal et al. (1990) two days after the earthquake. Based on damages, felt reports and

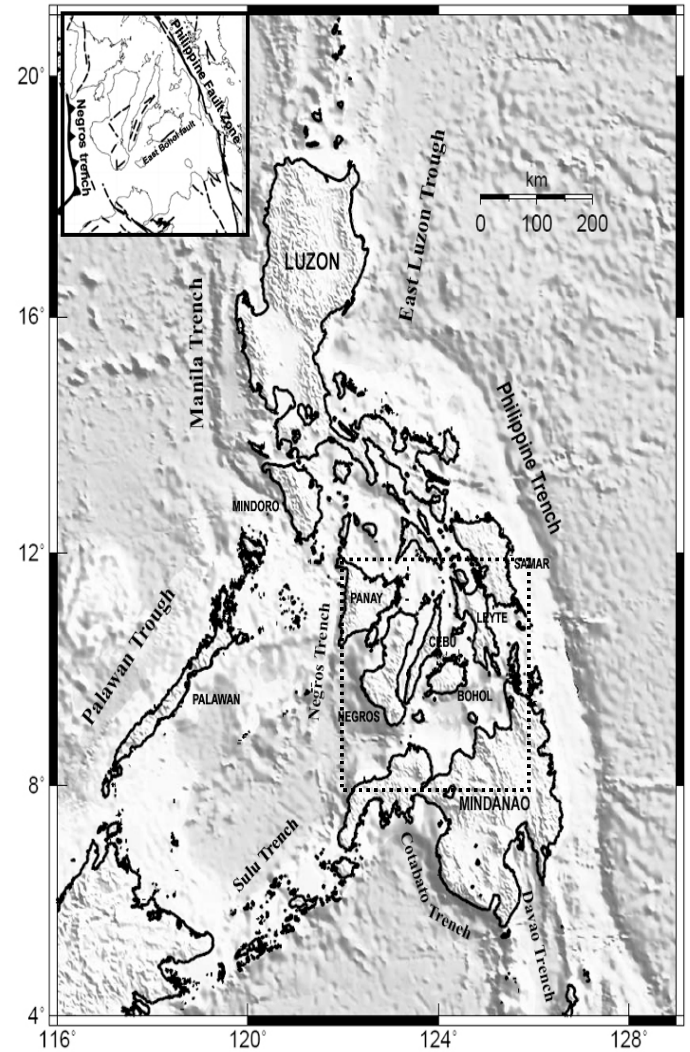


Figure 1: *The Philippine archipelago showing the Bohol Island in south central Philippines. Inset map shows the location of Negros trench, the PFZ and the East Bohol fault.*

experiences of local inhabitants, the maximum earthquake intensity was determined to be VIII on the PEIS or the Philippine Earthquake Intensity Scale (PHIVOLCS, 1996).

Bohol Island is located north of the Island of Mindanao in the southern portion of the Philippine Archipelago (Figure 1). The major structures that influence the tectonics in this region are the Negros Trench located west of Negros Island and the left-lateral strike-slip Philippine Fault Zone (PFZ) transecting the eastern part of Mindanao and Leyte Island. Within Bohol Island, the major structure is the northeast-southwest-striking fault called the East Bohol Fault (PHIVOLCS, 2000) shown in Figure 2, thatis probably related to the Alicia Thrust Fault (BMG, 1981). Bohol Island and adjoining areas had experienced moderate quakes in the past but were mostly lower than magnitude 5 and had no reported major impact on the island.

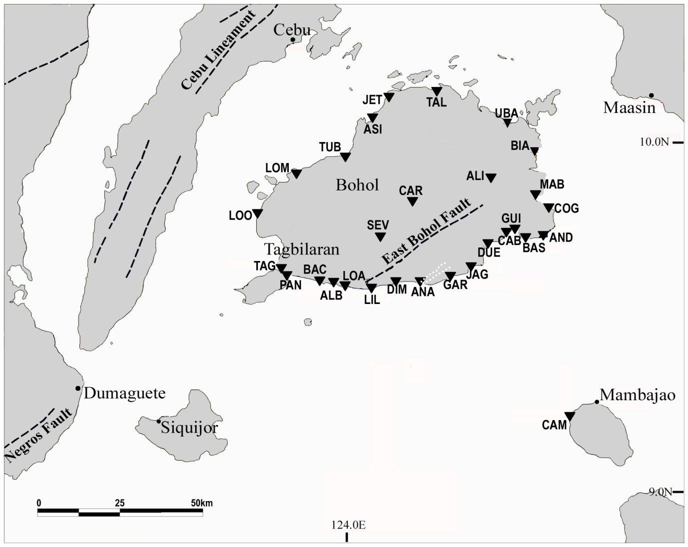
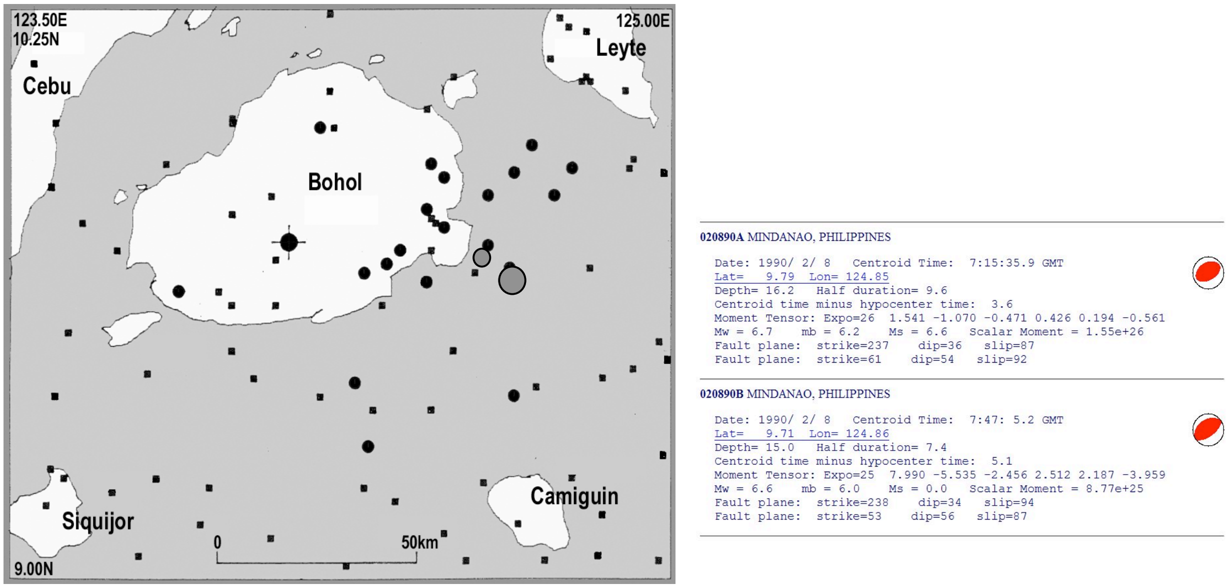


Figure 2: *Areas visited and/or with additional information regarding the 1990 Bohol quake used in this study (inverted triangles). Dashed white line shows the left-lateral ground rupture mapped by Umbal et al. (1990).*

The distribution of earthquakes prior to the 1990 event is rather diffuse and shows no distinct pattern (Figure 3). The preliminary location of the epicenter of the 1990 earthquake was placed 17 km east of Tagbilaran City that was on land and was attributed to the East Bohol fault (Umbal et al, 1990; PHIVOLCS, 2000). However, review of the Global CMT Catalog showed that there were two earthquakes of comparable magnitude on February 8 which occurred only about 30 minutes apart of each other. The second earthquake was also noted in Umbal et. al.'s (1990) report. The origin time, location and focal mechanisms of the two earthquakes are shown in Figure 3B. There was no surface rupture mapped along or associated with the East Bohol fault (EBF). In addition, the southeastern part of Bohol Island experienced a tsunami inundation (Umbal et al, 1990). Considering that the epicenter of the event was initially located inland, the mechanism and nature of the ensuing tsunami was not clear and has remained unexplained. The present study focuses on the seismic intensity and tsunami effects of the 1990 earthquake.



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020890A MINDANAO, PHILIPPINES

  Date: 1990/ 2/ 8   Centroid Time:  7:15:35.9 GMT
  Lat=   9.79  Lon= 124.85
  Depth= 16.2   Half duration= 9.6
  Centroid time minus hypocenter time:  3.6
  Moment Tensor: Expo=26  1.541 -1.070 -0.471 0.426 0.194 -0.561
  Mw = 6.7    mb = 6.2    Ms = 6.6   Scalar Moment = 1.55e+26
  Fault plane:  strike=237    dip=36   slip=87
  Fault plane:  strike=61    dip=54   slip=92

020890B MINDANAO, PHILIPPINES

  Date: 1990/ 2/ 8   Centroid Time:  7:47: 5.2 GMT
  Lat=   9.71  Lon= 124.86
  Depth= 15.0   Half duration= 7.4
  Centroid time minus hypocenter time:  5.1
  Moment Tensor: Expo=25  7.990 -5.535 -2.456 2.512 2.187 -3.959
  Mw = 6.6    mb = 6.0    Ms = 0.0   Scalar Moment = 8.77e+25
  Fault plane:  strike=238    dip=34   slip=94
  Fault plane:  strike=53    dip=56   slip=87
```

Figure 3: *a. Bohol island and the seismicity plot prior to the M6.2 earthquake in Bohol and vicinity (adapted from Umbal, et. al. 1990). Solid circle with cross indicated the epicenter (PHIVOLCS, 1990) while the solid black squares and circles indicate the seismicity from 1907-1988 and events from Feb. 9-28, 1990, respectively. Relocated epicenters and CMT solutions (b) are from the Global CMT Catalog for the 1515H event (A) and the event about 31min later (B).*

METHODOLOGY

Field surveys conducted in 2002 gathered data in many sites on Bohol island (Figure 2) to investigate and reevaluate the extent of tsunami inundation associated with the 1990 earthquake. Through eyewitnesses' interviews and field measurements, seismic and tsunami data were gathered and analyzed for the purpose of estimating earthquake effects as well as tsunami arrival times, runup heights and tsunami deposition/erosion features along the coast. Local inhabitants were interviewed

about their experiences during the ground shaking and their observations of the tsunami. Whenever possible, the specific sites mentioned during these interviews were further investigated to measure any remaining evidence of tsunami inundation and of maximum runup heights.

The interviews were conducted at regular intervals (ranging from 10 to 20 km) to assure uniform sampling points between communities along the coast. This information was needed to help illustrate the extent of the affected areas and perhaps indicate the most probable location of the tsunamigenic earthquake's source. Results were plotted and correlated with seismic intensity as this was essential in helping clarify tsunami source characteristics for future studies.

OBSERVATIONS AND RESULTS

The 2002 investigations and data collection were done for the eastern, southern and western sides of Bohol Island. Also, interviews were conducted along the north side of the island where damage and intensity had not as high. Additional information and data from Umbal et.al. (1990) were incorporated in the study. The accounts are given in Appendix I.

To protect the privacy of the people interviewed, their names were withheld and each account was labeled with letters W or M (signifying woman or man) with their age at the time of the interview shown in parentheses. From these accounts of ground motions and felt reports, seismic intensities were estimated. Similarly, information on observed tsunami heights were corrected from the predicted height of the Cebu tide gauge station (Mobile Geographics LLC, 2004-2009).

a. Seismic Intensity

Based on eyewitness interviews, it was determined that the quake's shaking lasted for about 3-7 seconds. Along the southeastern shores of the island, strong ground motions, widespread ground fissuring, landslides, subsidence and mud fountaining were responsible for most of the significant damage to the infrastructure of municipalities. Reportedly, a bridge collapsed and roads were closed by rockfalls. Figure 4a shows some of the damage.

Remnants or repairs of century-old churches indicated the extent of severe ground shaking in numerous towns. Based on observations of ground shaking and the associated environmental damage, an isoseismal map was prepared (Figure 4b). High intensities with NE-SW orientation were concentrated along the southeastern part of the island. Mapped ground ruptures (Umbal et al., 1990) were located about 7 km south of the EBF (Figure 2) and west of the highest observed intensities.

b. Tsunami Runup Heights

The coastal topography of Bohol Island is complex, characterized by gentle slopes, steep cliffs, rivers and river inlets, reef areas and mangroves. During the 2002 investigation, a total of 12 maximum tsunami runup heights were determined. Since there was no local tide gauge at Bohol, the nearest tide gauge station in the region was at Cebu Island. Its record of tidal fluctuations during the 1990 event was used to correct the estimates of tsunami runup heights. Since actual record from Cebu station is unavailable at the present time, corrections were applied based on predicted tide level at the Cebu station from the Mobile Geographics LLC (2004-2009) relative to the mean sea level. Table 1 shows the tsunami runup heights for different locations shown in Fig. 5.

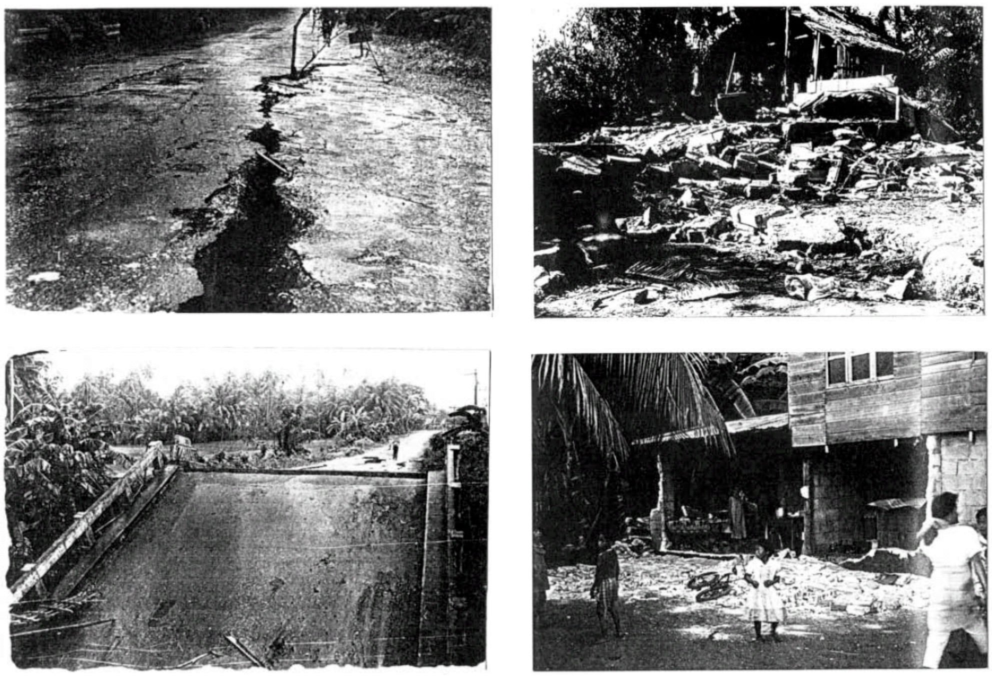

Figure 4a: *Photos adapted from Umbal et al. (1990) showing the damages at Guindulman (A), fault rupture near Anas (B), the collapsed bridge at Alijauan bridge at Jagna (C) and collapsed house in Candabang, Anda (D).*

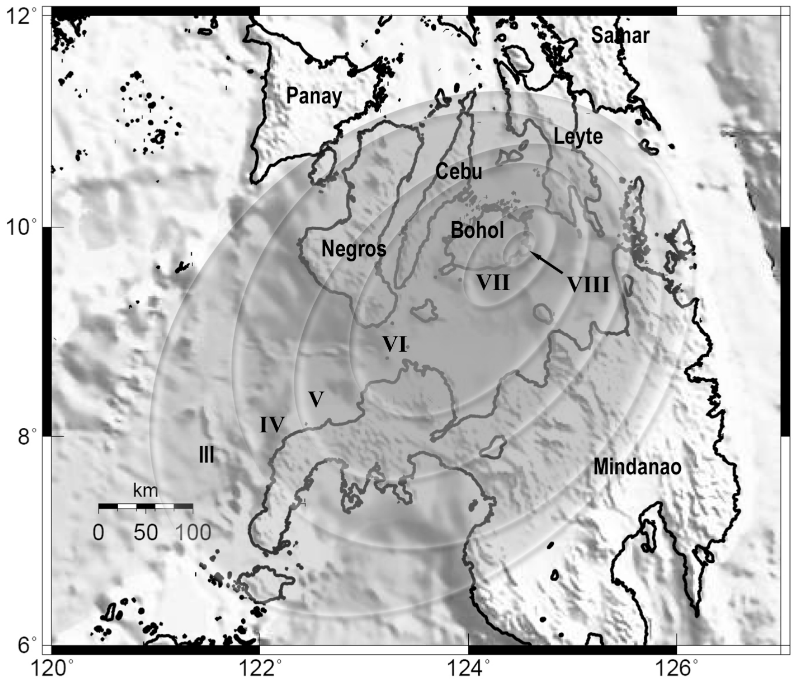

Figure 4b: *The earthquake intensity distribution of the 1990 Bohol earthquake based in this study and Umbal, et. al. (1990). Note the northeast-southwest elongation of the isoseismals.*

Table 1: Measured tsunami runup heights in southeastern Bohol measured after 12years of the tsunami impact.

No.	Place	Date Apr'02	Time (hh:mm)	Location	Measured height (m)	Location Code	PEIS Intensity
1	Ubay	17	15:55	124.461E, 10.058N	0	UBA	VII
2	Biabas	17	14:50	124.537E, 9.980N	0	BIA	VII
3	Mabini	17	11:50	124.522E, 9.867N	0.21	MAB	VII
4	Cogtong	16	15:15	124.524E, 9.842N	0.53	COG	VIII
5	Anda	16	14:20	124.562E, 9.735N	2.11	AND	VIII
6	Basdio	16	13:50	124.515E, 9.726N	1.08	BAS	VIII
7	Guindulman	16	12:30	124.481E, 9.762N	0.98	GUI	VIII
8	Cabantian	16	11:25	124.456E, 9.749N	1.52	CAB	VIII
9	Duero	16	10:15	124.402E, 9.711N	0.5	DUE	VIII
10	Jagna	16	09:45	124.361E, 9.651N	0.47	JAG	VIII
11	G. Hernandez	15	15:50	124.305E, 9.622N	0.32	GAR	VII
12	Anas	15	15:20	124.228E, 9.604N	0.31	ANA	VII
13	Dimlao	15	14:39	124.160E, 9.604N	0.49	DIM	VII
14	Lila	15	11:30	124.092E, 9.588N	0	LIL	VII
15	Loay	15	10:35	124.020E, 9.597N	0	LOA	VII
16	Alburqueque	17	08:30	123.988E, 9.602N	0	ALB	VII
17	Baclayon	15	09:40	123.950E, 9.608N	0	BAC	VI
18	Tagbilaran	18	09:25	123.852E, 9.635N	0.22	TAG	VI
19	Panglao	18	10:05	123.855E, 9.610N	0.31	PAN	VI
20	Camiguin	20	10:30*	124.628E, 9.221N	1.12	CAM	VI
21	Loon	20	15:20	123.780E, 9.806N	0	LOO	VI
22	Lomboy	20	14:30	123.886E, 9.918N	0	LOM	VI
23	Tubigon	20	12:30	124.011E, 9.967N	0	TUB	VI
24	Asinan	20	11:45	124.081E, 10.065N	0	ASI	VI
25	Jetafe	20	11:25	124.133E, 10.138N	0	JET	VI
26	Talibon	20	10:50	124.259E, 10.154N	0	TAL	VI
27	Sevilla	19	09:30	124.094E, 9.695N	0	SEV	VII
28	Carmen	19	11:30	124.219E, 9.835N	0	CAR	VII
29	Alicia	17	13:30	124.433E, 9.902N	0	ALI	VII

*Logged and recorded in the PHIVOLCS' Hibok-Hibok Volcano Observatory, retrieved via telephone interview.

Evidently, the 1990 earthquake generated small to moderate tsunami waves which affected the SE portion of Bohol (Figure 5). The maximum runup height of 2.11m was measured at AND that extends to MAB in the northeast and to TAG in the southwest. Between DIM and PAN, there were only reports of the sea level lowering, but no unusual increase in wave height or tsunami inundation. The reported tsunami at PAN and TAG could probably be due to possible island trapping effect (Yeh et al., 1994; As-Salek, 1998). It is noted that most notable tsunami runup heights were concentrated along the southeastern portion of Bohol Island - including a report from Camiguin island (CAM) of

1.2m based on PHIVOLCS official logs and records at the Hibok-hibok Volcano Observatory. The measured tsunami runup heights had an average height of 1m which was not sufficient enough to cause much destruction. The horizontal tsunami inundation was variable but generally extended to a few tens of meters from the shoreline. Fortunately, the local low tide at the time was low. If the tsunami had occurred at high tide inundation would have been at least 1m higher than what was observed.

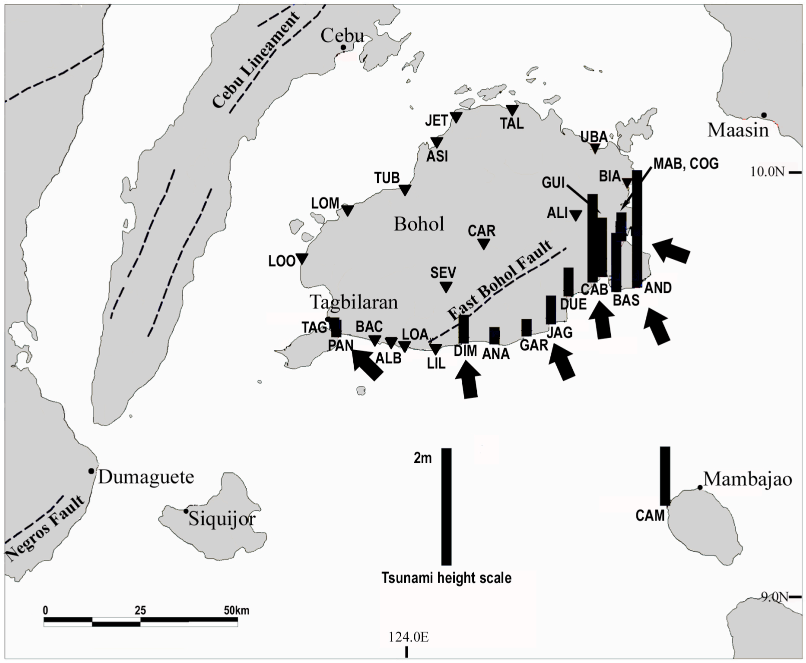

Figure 5: *Tsunami heights measured for the Bohol 1990 quake. Broad arrows indicate the observed direction of the incoming tsunami waves.*

b. Direction of Tsunami Propagation and Other Wave-related Observations

Based on eyewitness accounts, the main direction of the tsunami approach at AND and BAS was toward the north (N), toward NNW at DIM JAG and toward NW at PAN and COG. The direction of propagation indicated that the tsunami had its origin in an area southeast of Bohol. Eyewitnesses reported that the first wave throughout the southern shorelines of Bohol was associated with a depression in sea level. Accordingly, the southeastern shorelines of Bohol experienced a regional sea withdrawal of about 10-200m several minutes after the ground shaking stopped. In areas like BAC, ALB, LOA and LIL, some of the people indicated that the lowering in sea level occurred several minutes after the ground shaking, while others did not note an unusual change. At DIM and ANA, there was a rapid withdrawal of the sea, resembling low-tide, that trapped fish in the reef zone. The sea returned with foamy front and there were at least seven such oscillations. At GAR, however, there was only one wave observed which was 0.32m higher than the normal level. However, an eyewitness in JAG, remembered the trapped fish, cracks on the ground and sandboils when the water retreated three times about 150m away from the shoreline.

At GUI, many witnesses observed a drop in sea level several seconds after the ground shaking, accompanied by a rumbling sound. In this area many houses and boats were washed away by the tsunami when the water reached the town proper with a height of 0.98 m. In AND, the water receded 150-200 m from the shore, came back with a truck-like sound, foamy front and oscillated three times with the first wave being the biggest. In some portion of Anda town, the shoreline was protected by a 2-m high seawall where the tsunami was observed to have splashed over the seawall.

At COG and in MAB, there were observations of the sea receding, then rising about half meter in height several minutes after the ground shaking. Also, there were reports of the water turning muddy. Reportedly, the Alijuan River in DUE flowed inland due to force of the tsunami (Umbal et al., 1990). At TAG and PAN, the sea receded several minutes after the ground shaking then came back murky.

Generally, there was a recession of the sea immediately after ground shaking in the AND, BAS and GUI areas. However, in areas farther to the east and west relative to AND longer time elapsed before the retreat and return of the sea. The witnesses did not note any erosion or deposition of sediments along the shore. Although there were numerous reported landslides in the hills and some of the road were cut, there were no observations of landslides reaching the shore that might have displaced seawater. There were no reported observations of of sea water level changes along the northern part of the island

CONCLUSIONS AND FUTURE WORK

Damages from the 1990 Bohol earthquake were mainly due to intense ground shaking. However, tsunami inundation were observed and experienced at certain areas along the southeastern shores of Bohol Island. The highest seismic intensity was VIII on the X-point scale of PEIS of PHIVOLCS. The observed tsunami heights varied from 0.21-2.11 m and the waves reached also Camiguin Island. The extent of tsunami inundation varied because of the coastal morphology and the presence of barriers, but it was generally a few tens of meters from the shoreline along the southeast coast of Bohol. No notable erosion occurred and no deposition of tsunami sediments was observed.

On the other hand, The documented seismic intensity distribution and tsunami effects determined by this study indicate that the strongest ground shaking effects and devastation occurred in the southeastern portion of Bohol Island. This can be attributed to a possible offshore earthquake source or a submarine landslide induced by the earthquake. The strike of ground rupture correlates well with the elongated form of the earthquake's distribution of isoseismals. The rupture's location is west of both the highest observed intensities and of the observed tsunamis. Moreover, the ground rupture had a strike-slip fault mechanism consistent with thrust kinematics associated with EBF. It is also possible that the rupture extended offshore and that crustal displacements contributed to tsunami generation. However if we consider its location and kinematics, such possibility may be low. Thus, the notable incongruity between the quake's epicenter, the mapped ground rupture, the intensity distribution and the observed distribution of tsunami runup heights highlights the need for further investigation of the 1990 event. Closer scrutiny of aftershock epicenters, together with a source mechanism investigation may provide some clues on how the 1990 Bohol earthquake generated a tsunami.

Another interesting future effort would be a tsunami modeling simulation to verify if an offshore source may be possible. Similarly, an offshore landslide could be modeled to help determine if this was the source of the observed tsunami. Finally, based on the results of this study, we conclude that further investigation should be undertaken on the seismicity of the region and the distribution of earthquakes and aftershocks. Furthermore, a modeling study could help determine the tsunami's mechanism and explain the 1990 tsunami runup heights that were observed at both Bohol and Camiguin islands. Such additional investigations would be very helpful in improving disaster preparedness and mitigation for Bohol Island and would also increase awareness of potential tsunami hazards in the region.

ACKNOWLEDGMENTS

We express our gratitude to the inhabitants of Bohol Island for their kindness and support in unselfishly sharing their experiences and recollections about the 1990 earthquake and tsunami. We also thank Mr. Diding Salugsugan of PHIVOLCS Hibok-hibok Volcano Observatory for sharing the account from Camiguin island and to Mr. J. Umbal for his insights about the 1990 earthquake. This research was supported through the 2002 Tsunami Mapping and Hazards Assessment Program (TMHAP) of PHIVOLCS-Department of Science and Technology, in the Philippines. *This paper is dedicated to the memories of Drs. R.S. Punongbayan, N.M. Tungol, Mssrs. D. V. Javier, and O.S. Abengoza and especially to one of our co-authors, Dr. J.A. Daligdig.*

REFERENCES

Al-Salek, J.A. (1998), *Coastal Trapping and Funneling Effects on Storm Surges in the Meghna Estuary in Relation to Cyclones Hitting Noakhali–Cox's Bazar Coast of Bangladesh,* Journal of Physical Oceanography: Vol. 28, No. 2, pp. 227–249.

Besana, G.M., Tanioka, Y., Ando, M., Mirabueno, M.H., Manahan, J., De Ocampo, J., Perez, J., and Bautista, B. (2004), *The May 17, 1992 Earthquakes in Southeastern Luzon*, Geophys. Res. Lett., 31 L24618, doi:1029/2004GL020917.

Bureau of Mines and Geosciences (BMG). (1981), *Geology and Mineral Resources of the Philippines*, Dept. of Environment and Natural Resources, Quezon City, Philippines.

Harvard CMT Catalog at http://www.seismology.harvard.edu/CMTsearch.html

Imamura, F., Synolakis, C.E., Gica, E., Titov, V., Listanco, E., and Lee, H.J. (1995), *Field Survey of the 1994 Mindoro island, Philippines Tsunami*, Pure and Appl. Geophys., 144,3-4, 875-890.

Mobile Geographics LLC, 2004-2009, http://www.mobilegeographics.com/index.html.

PHIVOLCS, (1990), PHIVOLCS Earthquake catalog database, unpublished data.

PHIVOLCS, (1996), *Philippine Earthquake Intensity Scale* (PEIS), PHIVOLCS Poster.

PHIVOLCS, (2000), *Active Faults of the Philippines*, PHIVOLCS Published map.

Umbal, J.V., L.M. Masigla, R.N. Medrano, G.P. Diolata, (1990), *Report of Investigation on the Feb. 8, 1990 earthquake in Bohol Province*. PHIVOLCS Internal Report.

UH Sea Level Center, University of Hawaii,1000 Pope Road, MSB 317 Honolulu, Hawaii 96822-2336 at www: http://ilikai.soest.hawaii.edu and http://www.soest.hawaii.edu/UHSLC/

USGS-NEIC (2006), Earthquake Catalog Database. http://neic.usgs.gov/ neis/epic/epic_rect.html

Yeh, H., Liu, P.L-F., Briggs, M., and Synolakis, C.E. (1993), *Propagation and Amplification of Tsunamis at Coastal Boundaries*, Nature 372, 353-355.

APPENDIX I

At TAG, W1 (35) was inside her house when the earthquake struck. She felt the sideways ground motion and felt dizzy. She went outside, remembered that it was low tide at the time but about 4 minutes later she noticed that the water was bubbly and subsequently she heard a sound as the level rose to about .20 m. Another witness W2 (68), who was doing laundry when the earthquake occurred, also felt dizzy and held on to a post inside her house to steady herself. She remembered that the ground motion was sideways, sudden and lasted for about 5 seconds. She said that it was the strongest EQ she had experienced. However, nothing inside the house fell on the floor. She did not notice any fissure or mud on the ground. She also remembered that at that time it was low tide. Her house is about 20 m from the shoreline during the mean seal level. She said that the water retreated about 10m and came back “as high as a child” while motioning to the height of her child or up to her chest and noted that the water level increased by about 0.3m based on a banca (local wooden boat) that was floating nearby. After the ground shaking, the water retreated and came back muddy in a flood-like manner. She noted feeling at least 2 minor ground tremors, days after the strong initial quake.

At Baclayon Municipality (BAC), M1 (33) was inside his house (~30m from shore) and felt the sideways shaking during the main shock, followed by feeble shaking. He mentioned that the ground shaking lasted for about 4-5 seconds and that his whole family went outside. The street/road seemed to roll or behave in a wave-like fashion. He mentioned that according to the news, the municipalities of Valencia, Jagna and Guindulman Municipality were heavily affected and suffered more damage than BAC. He said that the waves seem to be stronger than normal. In this vicinity, we noted that the shore area is very flat with ~ 2m-high sea wall extending into the reef area as a ~150m-long groin. On the other hand, at Loay Fishport (LOA), M2 (48) reported that the earthquake shaking he felt was moderate while inside the house, noticed that the cabinets moved, but nothing toppled down. His house was ~ 150m from the seashore thus he did not observed the behavior of the sea. But his neighbors told him about unusual sea behavior. He did not remember seeing any fissures or cracks in their area. In Tocdog, Loay (also at LOA), M3 (30) observed that the sea was normal after the earthquake. There was no extensive damage, nor liquefaction was observed. He recalled that the ground shaking lasted for ~5sec. Their house was located right in front of the sea on the edge of the reef area. There was no panic among family members and neighbors during the ground shaking and nothing fell down inside the house.

In Lila Proper (LIL), M4 (42) was in his house along the shore and he felt sideways shaking motion for about 5s and became dizzy when standing. He said that the household items and furniture did not topple down and that he did not notice any abnormality in sea level. M5 (54), on the other hand, was inside the school about 2km from the shore during the earthquake. He reported that the sudden ground shaking lasted for about 5 seconds. Panicked, all the employees and the school children went outdoors. However, M6 (43) was along the shore when he felt a sudden ground shaking that lasted about 5 seconds and was able to observe about a 60m recession of the sea, approximately 2 minutes after the earthquake. The sea returned into its normal height after several minutes.

At Dimlao Proper (DIM), M7 (37) was near his “kubo”, a typical term used for hut, located right in front of the shore and edge of a reef. He was resting inside his house when the earthquake occurred at around 3pm. He felt a sudden jerk that lasted about 7 seconds and was unable to stand. The wall of the house - made of hollow blocks - collapsed. Another motion came after 5-7 seconds later and the sea retreated into a low-tide level, which is about 30m from the shoreline. It returned about 0.5m higher and 20m farther inland than the normal level and had a foamy front and “tunog na parang kumukulo” (boiling-like sound). He remembered that the sea oscillated at least 7 times and that rumbling sound was heard from the sea. The waves deposited fish, mud and seaweeds.

In Anas, Valencia (ANA), W3 (42) was inside her home and she felt the sideways shaking motion and held onto something to prevent herself from falling. She said nothing fell off from the shelf. The felt motion lasted for about 5 seconds and that immediately she went outside. She remembered feeling several ground shaking motions in the preceding days. Right after the first ground shaking, she went out near the shore where she met several neighbors who were also concerned about an impending “tidal wave”. They noticed that the sea level lowered to low-tide level and returned into its normal level but about 0.3m higher.

In Garcia Hernandez (GAR) where the flat reef is about 150m offshore, W4 (56) was inside her house that was made mostly of wood. The windows and cabinets shook while some bottles, TV, cabinets fell down from the wall. She got scared and thought that “katapusan na yata ito ng mundo” (it maybe the end of the world). She went out of the house immediately and dropped flat on the road and prayed. She observed that there was one strong shock and many less strong shocks afterwards. The shaking she felt was sideways and she observed the wave-like motion of the road. From the road, she saw that the water retreated about 5m from the former shoreline and left some fish stranded on the ground. Many small fissures (~4m long) and holes (0.2m wide) were observed all over the place. The sea returned back gradually but a little higher than normal (0.3m) and was accompanied with deep rumbling sound and foamy front. There was only one wave was observed at this locality.

In Jagna area (JAG), W5 (27) was at the school grounds near the shore practicing for the upcoming field day celebration. She felt the sideways ground shaking that lasted relatively long but can vaguely recall how many seconds. Some students panicked and jumped from second floor. There were many cracks in the school building and many fissures observed on the ground where water spurted out. The water in the sea retreated by about 150m and came back 0.5m higher than the normal level. She remembered that the sea retreated about 3 times.

In the community called Itum in Duero (DUE), W6 (48) was inside the house when she felt the sideways shaking and saw the fissuring on the ground. “Iba-iba ang dereksyon ng pag-uga” (The shaking directions were varied) and the whole place shook, undulated and moved like a wave. During the first strong shock, she had to hold onto a pole so as not to fall down. The cabinets toppled and plates fell and broke. Five to 10min after the shaking, the water in the sea receded and the neighborhood evacuated to a higher ground. There was no one left in the area, thus nobody was able to observe the return of the water. Some of her neighbors told her about the fissuring of the ground and seeing the ground opening and closing with hissing sounds. Ground shaking was observed and felt for about a week and the community stayed in the evacuation center during that period. She said that prior to this earthquake the BDCC (Barangay Disaster Coordinating Council) was unknown to them.

In Cabantian, Guindulman (CAB) M8 (71) - a community leader - was inside his wooden house when he felt an up and down shaking at first slow, then the vibration became stronger. He can vaguely recall but thought that it lasted about 5 seconds and that he saw ground fissure perpendicular to the road. Reportedly, the sea receded with rumbling sound, then came back at about 1.5 m higher than the normal level. He said the sea level was comparable to the usual low tide level and specifically that the water that came back like a high level tide, receding and returning in a way similar to heavy rains and flooding events.

At Guindulman Proper (GUI) W7 (42) was inside her house located about 15m from the shore when the up and down shaking occurred which lasted for about 10s and frighten her. The refrigerator toppled down. She went out and about 10min later noticed that the water receded about 15 meters from the shore. It came back and inundated the market which was a about 2 meters above sea level. , The water level at the market was about 0.5m high or 1m above the existing seawall. She also remembered many cracks along the highway near the gasoline station where mud came out. Thunder-like rumbling sound was heard during the shaking. Many less strong ground shakings were felt once in a while for about a month. Many houses were washed away and damaged especially those on stilts near the shore, while numerous boats were washed offshore. The bridge collapsed, the church was damaged and the church bell fell down.

At Basdio in Anda (BAS), M9 (48) was among the community leaders who were having a meeting at that time when they felt the ground shake. Everyonr dropped to the ground during the sideways shaking and they heard whooshing and rumbling sounds along with the ground motion. The aftershocks lasted for a week. He vaguely recalled how many seconds the ground shaking lasted but noticed that the water receded by about 100m from shore then came back with rumbling sound. The waves were 1m higher than normal with foamy fronts, retreated several times but subsequent waves were smaller than the first wave. Boats, houses and people were washed away and brought back by the wave activity. There were some cracks and rockfalls reported along shore.

M10 (46) was a member of the PDCC (Provincial Disaster Coordinating Council) residing in Anda poblacion (AND). A day before the quake, he heard an unusual sound. On February 8th he was at the 2nd floor of the Municipal Hall. Everybody panicked when the first strong sideways shaking was felt that lasted about 8 seconds followed by a much stronger shaking. The shaking was accompanied by rumbling sound. Ten minutes after the 2nd shaking, the sea receded by 50-60 m from the shore. The returning water came back carrying mud. In this area, the seawall is about 2m high and the normal high tide level reaches just at the sea-wall. After the earthquake, the wave that came back splashed into the sea wall. Perceptible aftershocks were felt for several days. People became concerned and stayed outside t for fear of "tidal wave". Others evacuated 1/2 km inland. M10 went to his barrio located about 1km from town proper, thus witnessed no other waves. The road was heavily damaged and the Municipal Hall suffered cracks. The water supply from the natural spring decreased to about 50%, probably due to cracks; this condition lasted for about a year.

In Cogtong at Candijay (COG), W8 (45) was inside her house when the earthquake struck. She noted that it was wave-like motion and not sideways. She became very afraid and could not remember how long the shaking lasted. She stayed on the ground. Canned goods in her "sari-sari" store fell down and the TV set was displaced from its original place. She heard neighbors talking about the "tidal wave" and they noticed that the sea was unusually high for that time of the day and the waves became stronger; everybody rushed further inland and was not able to see any other waves. In the same area, M11 (55), an owner of a store located near the bay, remembered that it was low tide at that time. He observed cracks inside his house/store appeared during the sideways shaking. Store goods toppled and fell down. The strong ground shaking was sideways and lasted for at least 4 seconds. After the earthquake, he noticed that the water receded by at least 10m. He noticed that the cemented area of the port suffered a crack and the level of the sea level increased and came back after 5 minutes, muddy and about 0.5m higher than normal. Aftershocks were felt for 3 weeks after the major shock. He remembered a small and generally weak shaking a day before February 8th.

At Mabini (MAB) M12 (47) was at the back of his house making a fish pen at about 100m away from fishponds. When he felt the ground shaking, he had difficulty standing and felt dizzy. He was surprised and stayed sitting down. He said that there were two shakes, several seconds apart. The second shaking was stronger than the first. The church bell rang softly. He went to the plaza after the initial shock. The stronger shaking was accompanied by a rumbling sound and small fissures appeared all over the place. At that time it was low tide but his brother-in-law told him that sea rose higher than normal (sudden high tide) and caused damage on the fish pens, cracking and collapsing some (mud) wall. In the same vicinity, M13 (22) was at school and noted small cracks on the ground after the ground shaking. He went outside and saw that the sea level was higher than normal (higher than the usual low tide level). He cannot recall how many seconds the shaking lasted. However, he remembered that the water at the fishpond became muddy. M14 (39) whose house is about 60m from the fishpond, was fishing at that time and heard rumbling sound thena sudden shaking and subsequent undulating sea motions. He could not recall the time interval between the shaking and the increase in sea water level. He also confirmed that there were two shakings, both accompanied by rumbling sound and that the second shake was stronger. After the shaking, the sea level abruptly increased. He paddled towards the shore, as water increased in height with boiling-like noise. He noticed that some trees were tilted and almost uprooted; the irrigation ditch suffered cracks and opened (not lateral displacement), no mud in cracks, the wave came in once like a flood.

At Alicia Town Hall (ALI), M15 (63) recalled that a rumbling sound preceded the shaking. He was unsure but he thinks that the shaking lasted about 6 seconds. He remembered seeing cracks at the back of the town hall that was located on a hill. At Biabas, Ubay (BIA), M16 (66) was making a "nipa" or palm roof when the earthquake occurred. He first heard a truck-like sound prior to the shaking motion. The glass windows fell down during the sudden and sideways motion. He was unable to stand and kept sitting down. He noted no fissure or cracks or any damage on the fishponds.

No one also observed any abnormality on the water level at the bay. W9 (55), who was a community chairman was inside her store. The shaking and the sound came simultaneously, store goods toppled down but there was no major damage on houses in the neighborhood. At Ubay, Poblacion (UBA) M17 (49) was in his house at the town proper and noted that the ground shaking lasted about 3s, that it was dominantly sideways and was accompanied with truck-like sound. In the same locality, one old house suffered cracks on its wall but there was no crack on the ground or any sign of liquefaction. The sea level was normal, low tide at that time and the public did not panic much. She said that the children went out of school buildings and classrooms and that the teachers guided them and made them drop on the ground. Some of the children were frightened.

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TSUNAMI- SEDIMENT SIGNATURES IN THE MANAKUDY ESTUARY ALONG THE WEST COAST OF INDIA

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ABSTRACT

The December 26, 2004 tsunami left its imprints along the southern coast of India especially the coastal areas of Manakudy in Kanyakumari district of Tamil Nadu. In the study area - Manakudy estuary - the post-tsunami sediment texture is predominantly coarser as inferred from textural analysis. Granulometric analysis indicates a shift of well-sorted, coarse skewed and platykurtic nature during the pre-tsunami season, to moderately sorted, fine skewed and leptokurtic behavior, after the tsunami. Violent hydrodynamic conditions have prevailed during the post-tsunami deposition of sediments. The unimodal nature of the post-tsunami sediments as distinct from the bimodal pre-tsunami sediments is reflected from the frequency curves. The CM diagram and the log probability curves confirm these observations.

1. INTRODUCTION

Sedimentological analyses of undisturbed surface sediments often provide a useful tool to unravel the mechanism of complex dynamic systems where transition between terrestrial and marine environment occurs. Granulometric analyses of unconsolidated sediments serve as an indicator of the depositional environment. Detailed knowledge of these processes is a prerequisite for the reconstruction of paleo-environmental changes from the sedimentary rock. The rate of sediment transport and accumulation in coastal environments are affected by tidal currents and river discharges (Hall et *al*., 1987). The sedimentary record is an integrated record of the pollution and also accounts for the process of diagenetic remobilization (Ridgeway and Price, 1987). Generally, during the monsoon season and heavy flooding, the accumulation rate of sediments is very high. However, during the post-monsoon season resuspension of minerals occurs because of shallow water depth and prevailing air currents (Jing Zhang *et* al., 1988). Texturally, the river sediments are sandy silt and are coarse grained, whereas in an estuary the sediments are clayey silt and fine grained (Muraleedharan Nair and Ramachandran, 2002) - though at the head of the estuary, sand is dominant. Grain size parameters such as mean size (M_Z) and standard deviation (S_D) reflect the energy conditions of the depositional environment (Visher, 1969; Sly Thomas and Pehetier, 1982) as the difference in size distribution is mainly due to variation in wave energy reaching the point of sampling and extent of turbulence affecting the environment. The coarser riverine sediments are moderately sorted while the finer estuarine sediments are poorly sorted (Mohan, 1995). Negative skewness (S_K) is characteristic of coastal environments that are undergoing erosion or non-deposition, while positive skewness characterizes the areas of deposition. Also, positive skewed sediments indicate an abundance of fine-grained sediments relative to the mean size (Datta and Subramanian, 1997). The variation in the kurtosis is a reflection of transport processes/depositional mechanisms of sediments (Baruah et al., 1997; Prabhakara Rao *et* al., 2001; Malvarez *et* al., 2001). However, during a rare geological event such as a tsunami, unpredictable changes are bound to occur in the granulometric characteristics.

Destructive cyclones are much more frequent in the Indian Ocean than tsunamis. However, the December 26, 2004 Sumatra earthquake, with a magnitude up to Mw9.3 generated the most destructive tsunami in recorded history, in terms of loss of life and property damage. The Manakudy Estuary is on the west coast of India and not in the direct path of the tsunami. Yet, the strength of the tsunami in this area was so enormous that a massive concrete bridge was uprooted and carried several hundred meters away. The impact in the estuary was rated as high compared to the low and medium categories assigned for most of the east and west coastal zones of India (Chandrasekhar et al., 2006). The sand ridges in the area, are indicative of a dynamic coast transgression and regression in the geological past. Bahlburg and Weiss (2007) reported that the sediments that were deposited by the tsunami along the coasts of Tamil Nadu were predominantly medium sands (350-700 μm) with a maximum thickness of 0.3m. In view of these observations, it was imperative to evaluate the dynamics of the tsunami's impact on the West coast of India, with further study of the grain size distribution in the Manakudy Estuary.

2. MATERIALS AND METHODS

The study area and sampling locations are depicted in Fig. 1. In August 2004 (pre-tsunami period) and in early January 2005 (post-tsunami period), eighty sediment samples were collected from 40 different locations using grab samplers. The sediment samples were homogenized and air- dried at 60° C to a constant weight. After the removal of carbonates, organic matter and possible iron oxides by wet sieving, the granulometric composition was determined using the pipette method (Folk, 1974; Gee and Bauder, 1986). Then, the values were fed into the ternary diagram (Shephard, 1954) and textural classifications were made. The grains were sieved in a Ro-Top machine with ASTM sieves from +45 to +230 mesh sizes so as to maintain quarter Φ interval and the various statistical parameters were evaluated.

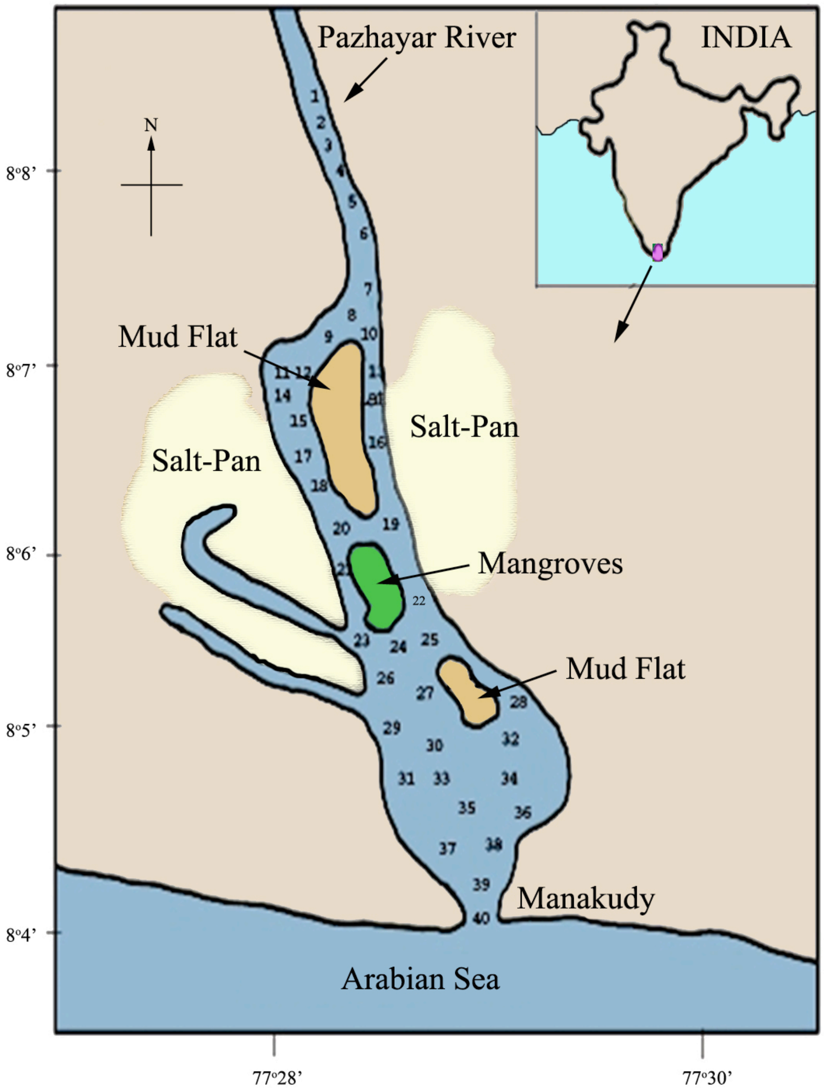
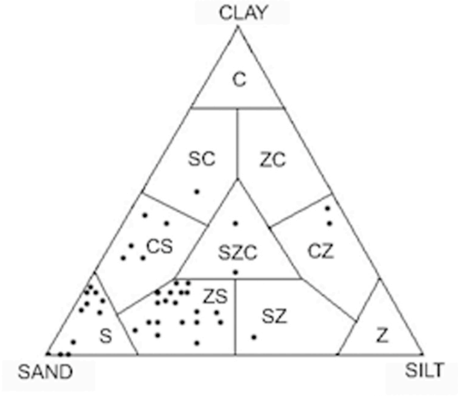


Figure 1: Sampling Area along Manakudy Estuary

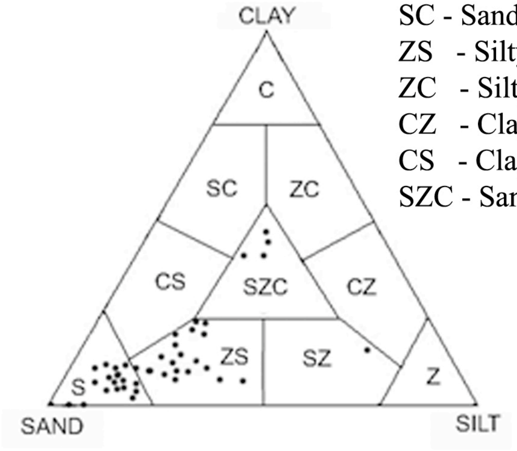
3. RESULTS AND DISCUSSION

Most of the sediments that were measured fall into four distinct textural classes: sand, silty sand, clayey sand and sand silt clay, as illustrated in the triangular diagram (Fig. 2). The silty sand alone constitutes nearly 50% of the samples collected before and after tsunami. The high silt content in general, could be attributed to flocculation, followed by fine colloidal aggregates settling during estuarine mixing in the post-tsunami sediments (Kranck, 1975).



a) Pre-tsunami

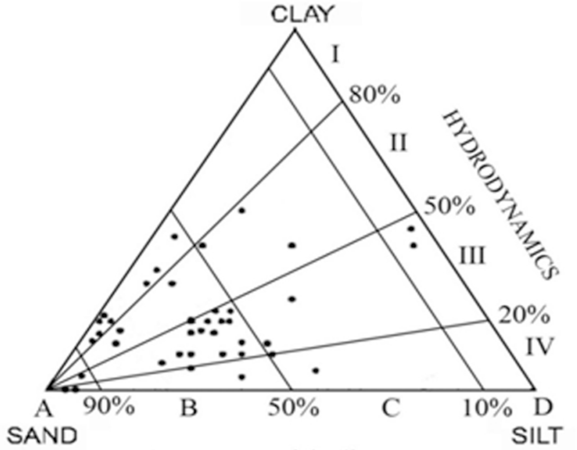
S - Sand
Z - Silt
C - Clay
SZ - Sandy Silt
SC - Sandy Clay
ZS - Silty Sand
ZC - Silty Clay
CZ - Clayey Silt
CS - Clayey Sand
SZC - Sand -Silt - Clay



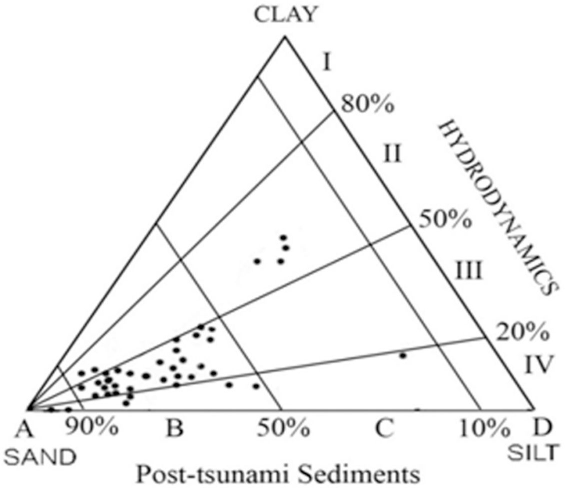
b) Post-tsunami

Figure 2: Textural classification - Triangular diagram

According to Morten Pejrup (1988), a constant clay/mud ratio can explain different degree of flocculation of the suspended sediment, which in turn is strongly influenced by turbulence of the estuary. The line of constant clay content can be used for a simple description of the hydrodynamic condition during sedimentation. The decreasing clay content from sections I to IV in the diagram (Fig.3) would indicate increasingly violent hydrodynamic conditions. High clay content in the mud fraction, would represent a quiet hydrodynamic condition. Over one third of the pre-tsunami sediments have populated segments I and II, indicating high clay content and relatively calm hydrodynamics. On the other hand, most of the post-tsunami sediments are confined to lower clay segments III and IV, indicating more violent hydrodynamic conditions during sedimentation.



Pre- tsunami Sediments



Post-tsunami Sediments

Figure 3: Hydrodynamics of Manakudy Estuary

The grain size statistics are used to distinguish between high and moderate energy environments. The grain size distribution is controlled by the physical transportation of sediment, including sediment aggregation and deposition, gravitational circulation, tidal pumping and tidal trapping (Wai *et* al., 2004). Grain size distribution of estuarine sediments has unraveled the existence of statistical relationships between the different size characteristics such as mean size, standard deviation, skewness and kurtosis. All the statistical parameters have been arrived at for all samples using the graphical method in which the cumulative weight percentage vs. quarter Φ values are plotted on a log probability chart to give the percentiles, followed by calculations (Table 1).

Mean size is an index to measure the nature as well as the depositional environment of the sediments. It represents the average size of the sediments influenced by the supply, transporting medium and the energy conditions of the depositing environment. The mean grain size (Φ) ranges from 0.98-2.37 in the pre-tsunami samples and 0.87- 2.07 for post-tsunami sediments. The mean diameter also indicates that most of the sediments in the pre-tsunami consist of very fine sand. The mean size indicates that the fine sands were deposited at a moderately low energy conditions. The decrease in size for the post-tsunami sediments may be due to a variation in wave energy reaching and the extent of turbulence affecting the environment due to the tsunami waves. The variation in Ø, therefore, reveals the different energy conditions which lead to the deposition of these kinds of sediments.

Standard deviation measures the sorting of sediments and indicates the fluctuations in the kinetic energy or velocity conditions of the depositional agent. The standard deviation ranges from 0.32 to 0.96Φ for the pre-tsunami and 0.56 to 1.04 Φ for the post-tsunami sediments respectively. The pre-tsunami sediments fall into the well sorted to moderately well sorted region, while most of the post-tsunami sediments are in the moderately sorted region. This sorting nature of the sediments may be due to the intermixing and influx of the sediments from sea as well as the river. The presence of fine sand and the well-sorted nature suggests effective wave action to scour the sediments during the break of tsunami waves.

Skewness measures the asymmetry of the frequency distribution. The values of skewness in the Manakudy estuary range between -0.51 and + 0.4 for pre-tsunami and -0.04 to +0.37 for post-tsunami sediments indicating that the normal size distribution is influenced by finer sizes (fine skewed). Skewness is positive (fine skewed) in the post-tsunami, whereas both positive as well as negative (coarse skewed) in the pre-tsunami season. The symmetry of the samples varies from fine skewed to coarse skewed nature. The fine skewed sediments generally imply the introduction of fine material or removal of coarse fraction or winnowing of sediments (Duane, 1964). The post-tsunami sediments have been deposited under high energy conditions as indicated by the positive skewness (fine skewed) compared to the pre-tsunami samples which are coarse skewed at the tail of the estuary, an indication of deposition under calm conditions.

Kurtosis measures the ratio between the sorting in the tails (leptokurtic) of the distribution and sorting in the central portion (mesokurtic) of the distribution and better sorted than the central portion (platykurtic) in the distribution. Kurtosis varies from 0.69-1.47 in the pre-tsunami and 0.77-1.44 in the post-tsunami seasons respectively. Most of the pre-tsunami sediments are platykurtic to mesokurtic while post-tsunami sediments are leptokurtic to mesokurtic. Jaquet and Vernet (1976) have used

Table 1. Grain Size Parameters

Sample No.	Pre-tsunami				Post-tsunami			
	M_z	S_D	S_k	K_G	M_z	S_D	S_k	K_G
1	2.35	0.78	-0.21	0.94	1.31	0.62	0.03	0.99
2	2.37	0.81	-0.19	0.94	1.80	0.79	0.33	1.34
3	2.33	0.95	-0.27	1.06	1.02	0.87	-0.04	1.23
4	1.68	0.40	-0.05	1.23	1.14	0.80	0.30	1.10
5	1.62	0.92	0.09	0.905	1.66	0.95	0.15	0.93
6	1.77	0.91	-0.16	0.86	1.89	0.92	0.19	0.81
7	1.21	0.84	-0.18	0.99	1.14	1.04	0.02	1.04
8	1.67	0.35	0.03	1.22	1.45	0.81	0.11	1.36
9	2.27	0.66	-0.29	0.84	1.38	0.77	0.13	1.07
10	2.25	0.72	-0.51	0.77	1.12	0.83	0.07	1.44
11	1.67	0.76	-0.15	0.98	0.98	0.70	-0.01	1.04
12	1.70	0.78	-0.10	0.72	1.40	0.65	0.10	1.22
13	1.86	0.70	-0.13	0.91	1.41	0.66	0.08	1.42
14	2.37	0.60	-0.41	0.90	1.13	0.87	0.21	1.04
15	1.88	0.76	-0.13	0.99	1.41	0.67	0.08	1.14
16	2.14	0.69	0.21	0.86	1.57	0.69	0.18	1.33
17	1.93	0.76	-0.03	0.88	1.76	0.75	0.11	0.92
18	1.90	0.82	0.22	0.87	0.87	0.99	0.11	1.15
19	1.55	0.51	-0.03	1.10	1.22	0.89	0.26	1.10
20	1.80	0.81	0.16	1.01	1.12	1.00	0.06	0.85
21	1.85	0.64	0.26	1.08	1.18	0.94	-0.03	1.03
22	1.82	0.72	0.15	0.99	1.28	0.52	0.10	1.10
23	1.97	0.70	0.34	0.88	1.23	0.64	0.08	1.13
24	1.72	0.54	0.29	1.43	1.69	0.73	0.20	1.30
25	1.90	0.57	0.35	1.03	1.39	0.64	0.11	1.26
26	1.63	0.44	-0.13	1.41	1.57	0.79	0.19	1.40
27	0.98	0.86	-0.09	0.69	1.36	0.68	0.09	1.20
28	1.78	0.32	0.20	1.47	1.16	0.60	0.07	1.11
29	2.13	0.73	0.15	1.05	1.32	0.56	0.04	1.08
30	1.62	0.61	0.28	1.30	1.23	0.80	-0.03	1.16
31	2.08	0.77	0.25	0.90	1.33	0.71	0.14	1.38
32	1.91	0.73	0.40	0.79	2.07	0.99	0.14	0.77
33	2.14	0.82	0.29	0.78	1.30	0.88	0.10	1.10
34	1.88	0.77	0.22	0.81	2.00	0.99	0.18	0.85
35	2.00	0.61	0.28	0.84	1.73	0.89	0.24	1.23
36	2.03	0.69	0.13	0.82	1.53	0.82	0.19	1.20
37	2.04	0.66	0.25	0.92	1.70	0.93	0.37	0.93
38	2.26	0.65	0.10	0.92	1.33	0.65	0.14	1.34
39	2.06	0.44	0.19	0.97	1.54	0.82	0.19	1.26
40	2.06	0.96	0.26	0.83	1.32	0.82	0.02	1.09

M_z-Mean Size, S_D-Standard Deviation, S_k-Skewness, K_G-Kurtosis graphic kurtosis to recognize the characters of population, as strongly platykurtic curves are found to be bimodal with sub equal amounts of the two modes. The frequency distribution curves of the pre-tsunami sediments have confirmed the bimodal-platykurtic behavior of the sediments and the post-tsunami unimodal sediments are mesokurtic to leptokurtic (Fig.4).

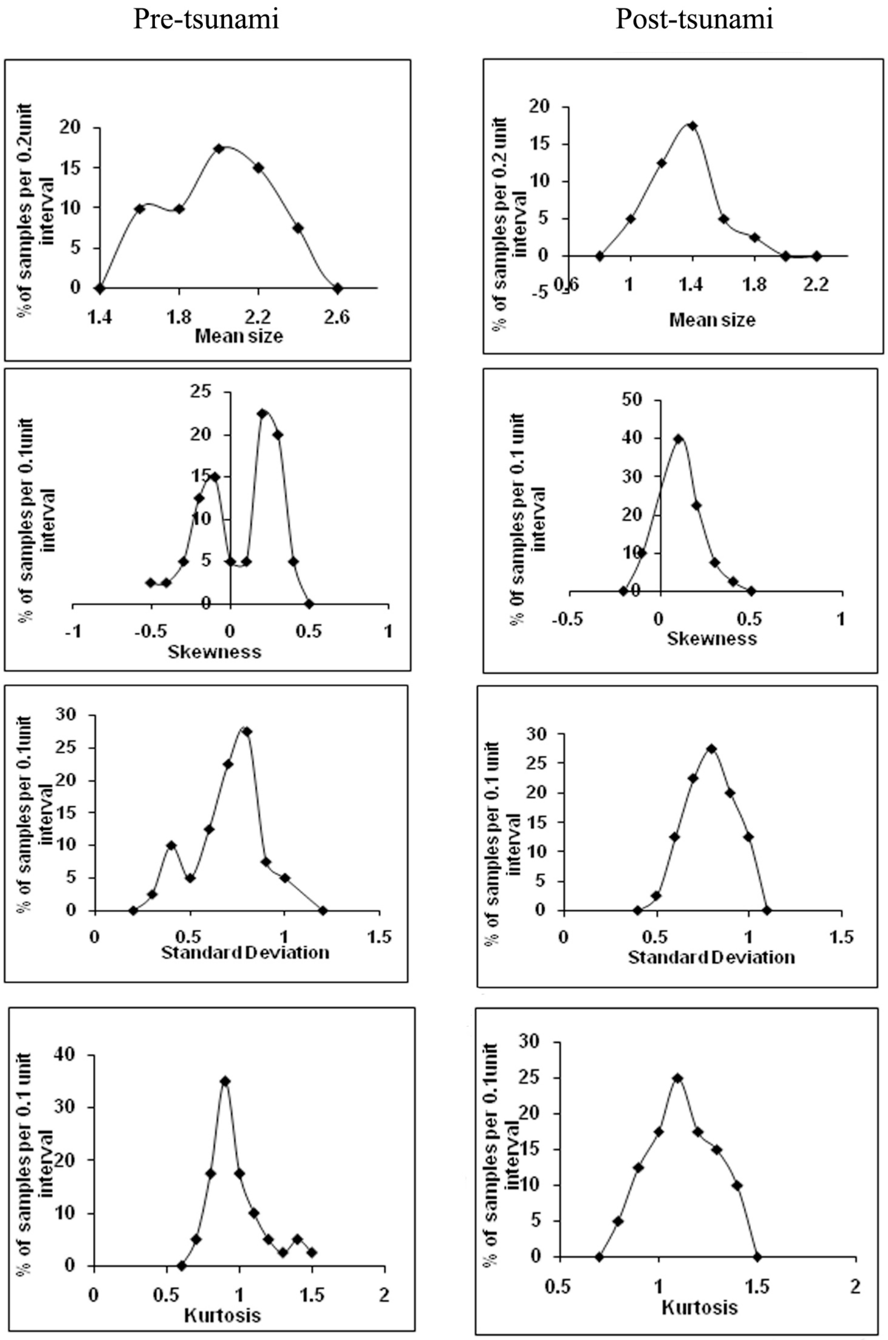


Figure 4: Frequency Distribution Curves (Samsuddin,1986)

The modal behavior is further confirmed by the frequency curves of Folk (1974), as depicted in Fig. 5.

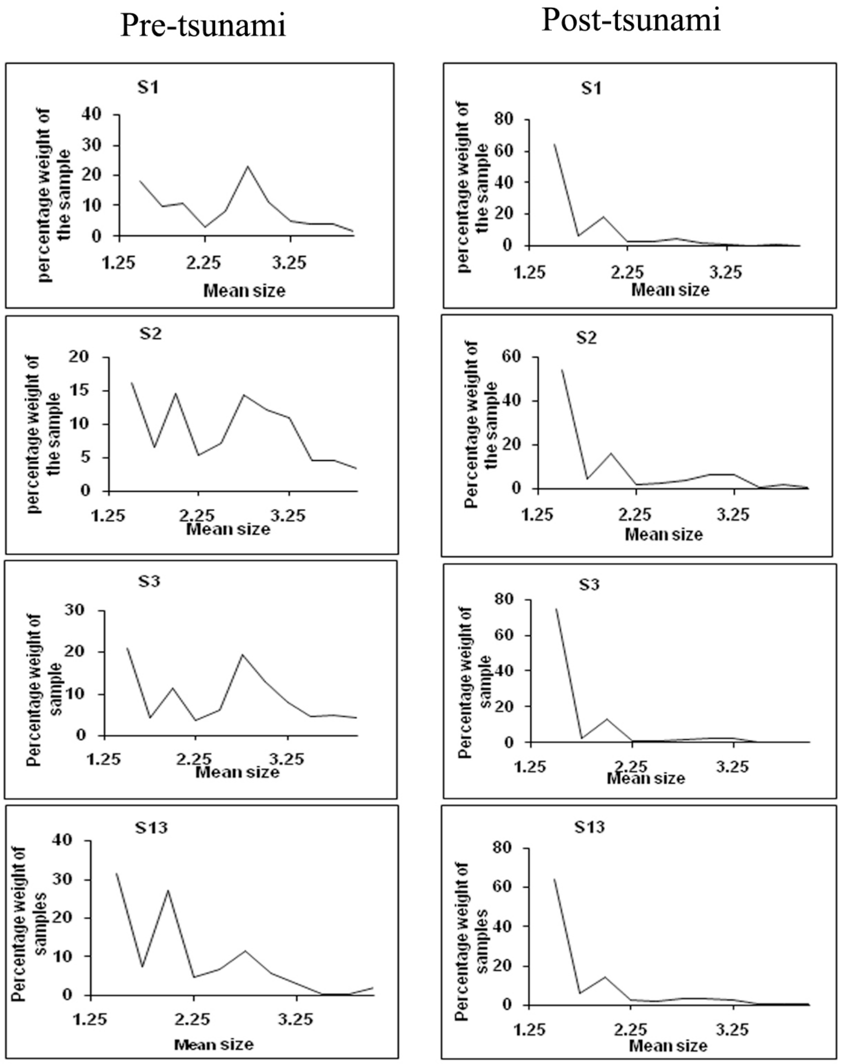


Figure 5: Frequency Curves (Folk, 1974)

The bivariate plots Fig. 6 (a-f) also confirm the above observations, as seen from the distinct different behavior of post-tsunami sediments.

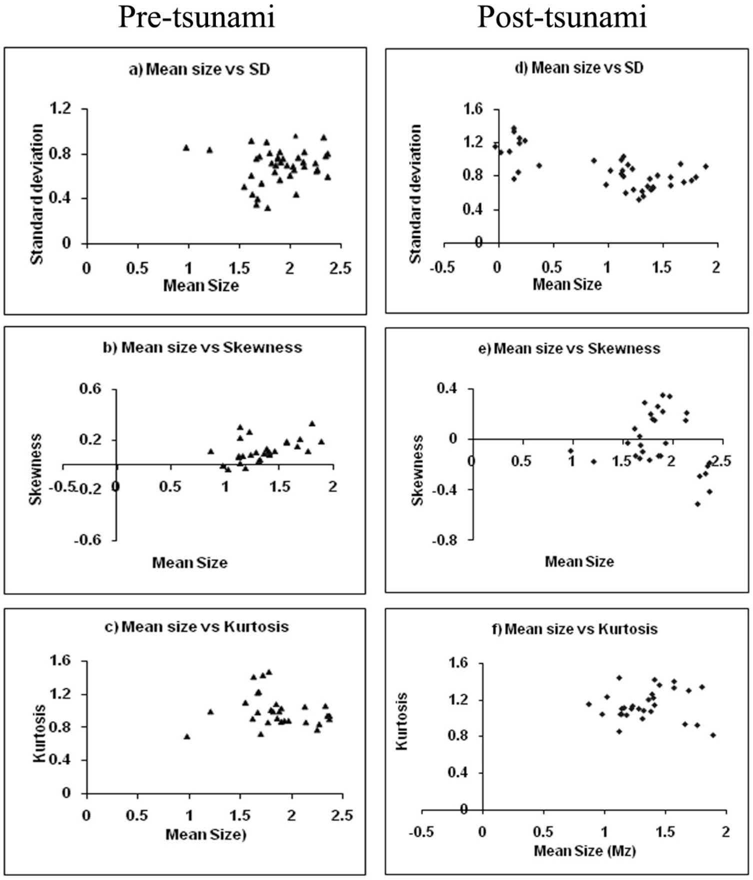
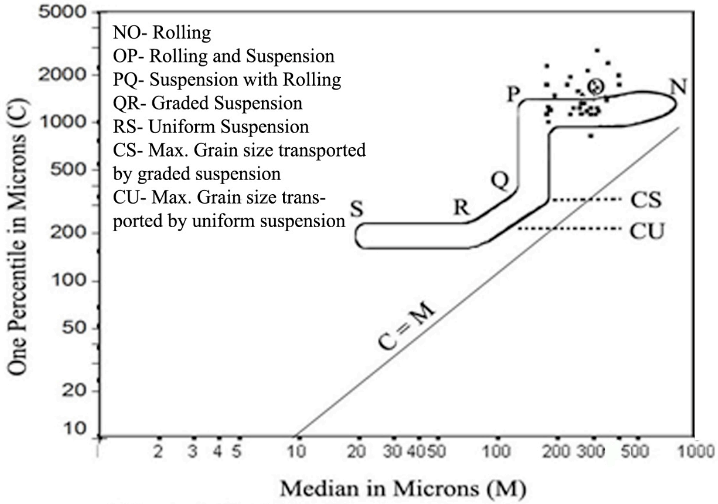
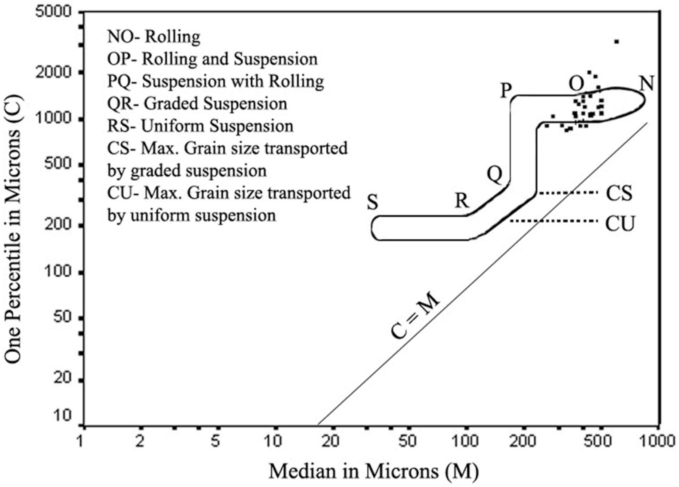


Figure.6. Bivariate plots- Pre-tsunami vs Post-tsunami

The C=M pattern offers a platform for deducing transportation modes of sediments. The area of a complete C=M pattern may be divided into sections which are related to sedimentary environments. The location of the plotted points for a single deposit within the area of a complete C=M pattern indicates the probable conditions of transport before deposition. In the pre-tsunami and post-tsunami patterns for the sediments of Manakudy estuary (Fig.7) the OPQ segment is populated indicating mostly the estuarine characteristics of the sediments (Ramanathan et al.2009). Some of the sediments are found in the high turbulent discriminate OP, and the less turbulent discriminate PQ, are indications of rolling of the sediments with suspension as well as suspension with rolling. Most of the sediments during the pre-tsunami season fall outside OPQ parallel to C=M between 200 and 400 microns indicate good sorting as established elsewhere. The post-tsunami sediments have two distinct segments NO and OP strongly populated, which is an indication that the majority of the sediments are transported by rolling and a small part by rolling and suspension. Some of the post-tsunami sediments are falling outside NOP segments shows a considerable influence by the marine currents under post-tsunami conditions. Moreover, C is above 1000 microns (1000-3000 microns) for most of the post-tsunami sediments infer violent hydrodynamic condition prevalent due to tsunami tidal waves, leading to coarser sandy deposition.



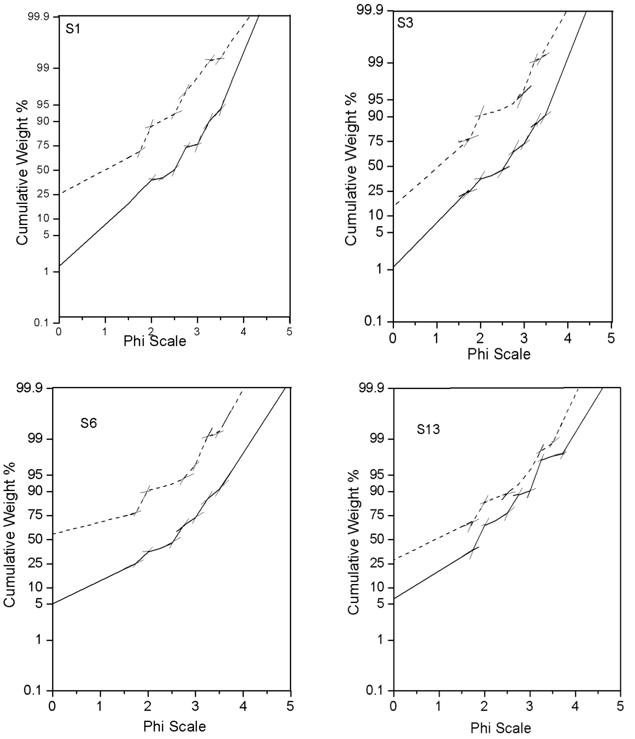
a) Pre-tsunami



b) Post-tsunami

Figure 7: C=M Pattern of Sediments

The log probability distribution curves have been used to recognize the different populations (Visher, 1969) suspension, saltation and surface creep (traction). The grain size pattern of the log probability curves (Fig. 8) shows at least three segments each defined by four control points (Weltje and Prins, 2007). Each population is truncated and joined with the next population to form a single distribution, as grain size distributions do not follow a simple log normal law but are composed of several log-normal populations with different mean and standard deviation. Hence each transportation process is reflected in a single grain size distribution plot with different percentage of population, degree of mixing, size range and degree of sorting providing insight into the currents, waves, rate of deposition and provenance.



-----Pre-tsunami - - - -Post-tsunami

Figure. 8. Vishers log Probability curves

The high saltation population (>50%) for the pre-tsunami grains reveals calm conditions prevailing during pre-tsunami period. On the other hand for post-tsunami grains, saltation population is low (<30%) which is indicative of violent hydrodynamic conditions. The position of the truncation point may also reflect the turbulent energy conditions at the depositional interface. The post-tsunami sediments have a very fine truncation point for the saltation population (3.5-3.6) revealing violent energy conditions. Also strong mixing of the suspension and saltation population indicates highly variable energy conditions. Hence it is established that the sediment transport occurs from the estuarine mouth due to winnowing action of the oscillatory waves followed by tidal action, which is an intermediate characteristic between those of fluvial and beach sediments during pre-tsunami season. The deposition of post-tsunami sediments is due to the erosion and transportation of sandy sediments from the backwash of the tsunami wave.

4. CONCLUSIONS

The pre-tsunami sediments are bimodal and fine (silty sand) compared to the unimodal and coarser (sand) behavior of the post-tsunami deposits. The post-tsunami grains bear marine characteristics under violent hydrodynamics, whereas the pre-tsunami grains are mostly fluvial, deposited under low energy conditions. The tsunami signatures are witnessed in the post-tsunami texture of the sediments as established from the statistical parameters of the grains. Their deposition under high-energy conditions is further evident from the C=M pattern and Vishers diagram.

REFERENCES

Bahlburg, H.Weiss, R.2007.Sedimentology of the December 2004, Sumatra tsunami deposits in eastern India (Tamil Nadu) and Kenya Int. J. Earth Sci.96, 1195-1209

Baruah .J kotoky. P and Sarma J.N (1997): textural and geochemical study on river sediments: A case study on the Jhanji River, Assam. Jour Indian Assoc. Sedimentologists.16.p.195-206

Chandrasekhar, N. Loveson, V.J. and Rajamanickam, G.V, 1996. Distribution of organic matter and calcium carbonate content in the sediments of salt-marsh area, Tuticorin Gulf of Mannar, J. Indian Association of Sedimentologists, V.15, No.1, pp.59-66

Chandrasekar, N. Saravanan, S. Immanuel, L. Rajamanickam, J. and Rajamanickam, G.V. (2006) Classification of tsunami hazards along the southern coast of India: An initiative to safeguard the coastal environment from similar debacle. Science of Tsunami Hazards, Vol. 24, No. 1, page 3 (2006)

Datta.D.K. Subramanian., 1997. Texture and Mineralogy of sediments from the Ganges-Brahmaputra-Meghna river system in the Bengal Basin, Bangladesh and their environmental implications, Environmental Geology 30(3/4)

Duane, D.R.1964. Significance of skewness in recent sediments, Western Pamlico Sound, North Carolina, J. Sediment, Petrol, 34:864-874

Folk, R.L. and W.C.Ward.1957, Brazos River bar: a study in the significance of grain size parameter. J Sedimentary Petrology, 27:3-26.

Gee, G.W. and Bauder, J.W.1986. Particle size Analysis. In: A. Klute. Methods of Soil Analysis.part1: Physical and Mineralogical Methods, 2nd edition ASA and SSSA, Maidison, WI. pp, 383-411.

Hall, M.J, Nadeau, J.E and Nicilich, M.1987. The use of trace metal content to verify sediment transport from Delaware Bay on to the New Jersey inner shelf, J. Coastal Res V.3, pp 469-474

Jaquet, J.M. and Vernet, J.P. (1976) Moment and graphic size parameters in the sediments of Lake Geneva, Switzerland, J. Sediment Petrol, V. 46 p.305-312

Jing-Zhang, Weiwen Huang and Jean Marie Martin.1988, Trace metals distribution in Huange (Yellow River) Estuarine sediments Estuarine Coastal and Shelf Sci.V.26, pp.499-516

Kranck 1975 Sediment deposition from flocculated suspensions, Sedimentology, V.22, pp.111-124

Malvarez, G.C., Cooper. J.A.G. and Jackson D.W.T (2001): Relationship between wave induced currents and sediment grain size on a sandy tidal flat. Jour.Sed.Research.71, p.705-712

Mohan, P.M. 1995. Distribution of heavy minerals in Parangi pettai (Port Nova) Beach Tamil Nadu Journal Geological Society of India.46: 401-408.

Moore, A. Nishimura, Y. Gelfenbaum, G. Kamataki, T.Triyono, R.2006. Sedimentary deposits of the 26 December 2004 tsunami on the northwest coast of Aceh, Indonesia. Earth planets Space 58,253-258

Morten Pejrup (1988) the triangular diagram used for classification of estuarine sediments: A new approach. Tide Influenced Sedimentary Environments and Faces, p.289-300

Muraleedharan Nair, M.N., Ramachandran, K.K., 2002.Textural and trace metal distribution in sediments of Beypore estuary. Indian J. of Mari Science, 31:295-304.

Prabhakara Rao.A. Anilkumar.V, Yugandhar Rao.A Ravi G.S and Krishnan.S (2001): Grain size parameters in the interpretation of depositional environments of coastal sediments between Bendi Creek and Vamsadhara River, East Coast, India, Jour. Indian Assoc. Sedimentologists. V.20.no. 1.p. 106-116.

Ramanathan, A.L Rajkumar, K. Jayjit Majumdar.Gurmeet Singh, Behra, P.N Santra, S.C and Chidambaram, S.2009. Textural characteristics of the surface sediments of a tropical mangrove sundarban ecosystem India Indian Jour. of Mar. Sci vol.38 (4), p.397-403

Ramkumar, M., P. Sudha Rani, Gandhi, M.S., Pattabhi Ramayya, M 2000 Textural characteristics and prepositional sedimentary Environments of the Modern Godavari Delta. Jour. Geol. Soc. of India, V. 56, pp. 471-487.

Ridgeway, I.M. and Price, N.B. (1987) geochemical associations and post-depositional mobility of heavy metals in coastal sediments: Loch Etive, Scotland. Marine Chemistry v.21, p. 229-248

Samsuddin (1986) Textural differentiation of the foreshore and breaker zone sediments on the Northern Kerala Coast, India.Sediment.Geol.V.46, p.135-145

Shepard, F.P. (1954) Nomenclature based on Sand-Silt-Clay ratios.J.sed.Pet.v.24.p.155-158.

Sly, P.G., Thomas, R.L and Pelletier, B.R (1982) Comparison of sediment energy-Texture relationships in marine and lacustrine environments HydrobiologiaV.91, p.71-84

Wai, O.W.H. Wang, C.H., Li, Y.S., Li, X.D., 2004.The formation mechanisms of turbidity maximum in the Pearl River estuary, China Marine Pollution Bulletin 48, 441-448

Weltje, G.J and Prins, M.A., 2007.Geetically meaningful decomposition of grain size distributions. Sedimentary Geology 202.409-424.

Visher, G.S. (1969): Grain size distribution and depositional process. Jour. Sed. Pet., 39.p. 1074-1106.

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THE ROLE OF MEDIA IN SCIENCE AND TECHNOLOGY EDUCATION, DEVELOPMENT AND REHABILITATION OF WOMEN AFFECTED BY THE 2004 TSUNAMI IN THE OF THE STATE OF TAMILNADU

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ABSTRACT

The great Sumatra earthquake of 26 December 2004 generated a destructive tsunami which devastated coastal communities bordering the Indian Ocean, killing thousands of people in Indonesia, Sri Lanka, India, Thailand, Somalia, Myanmar, the Maldives, Malaysia, Tanzania, Seychelles, Bangladesh, South Africa, Yemen and Kenya. It was one of the deadliest natural disasters in modern history. In India, the death toll and damages were severe, particularly along the southern and eastern coastal regions. Subsequently, central and state government authorities in the state of Tamilnadu - one of the most severely stricken regions - took immediate measures for tsunami preparedness and rehabilitation. The media played a major role in this effort by communicating to the public information related to the science and technology facts of tsunami hazards and to ways of mitigating their impact with better understanding and preparedness. Through its superior ability to communicate effectively information, the media became the role model in helping people make decisions for their own welfare. The present study was undertaken for the purpose of determining the media's role in the post-rehabilitation efforts and particularly in improving the status of affected women of the north Chennai region, who were forced to migrate from Ernavour and Ennore, in Chennai district, in the India state of Tamilnadu, by providing them science and technology communication.

Keywords: *India; tsunami; media; preparedness; rehabilitation; post-disaster; education.*

1. INTRODUCTION

The physical characteristics of tsunamis and their impact on coastal communities are well known and adequately described in the scientific literature (Lorca et al., 1997). Along the coastal areas of south India the 2004 tsunami caused serious damage and numerous deaths. The majority of the victims were women and children. Subsequently and over a period of time, local government authorities searched for solutions to help the people who were adversely impacted by the tsunami, in spite of objections to rehabilitation efforts by various political parties and NGOs.

After the tsunami disaster struck the region, people faced many problems due to lack of information and of awareness about available resources. Their lifestyles had been totally altered by losses of relatives, of properties and by the disruption of daily routine activities. As a result, mass media became the essential form of communication for such people who were in search of survivors and for ways to meet their basic needs for food, shelter and safety. Thus, the media assumed a major role in the post-tsunami rehabilitation efforts in Tamilnadu. Furthermore, through effective and essential communication, the media helped inform and educate people about the tsunami hazard - thus enhancing their awareness and the need for disaster preparedness. The present study analyzes the role of the media in improving the rehabilitation status of women in the severely impacted region of North Chennai by communicating effectively information to those who immigrated from Ernavour and Ennore, Chennai, on Tamilnadu.

1.1. The 2004 Tsunami in the Chennai District.

The great earthquake occurred off the western coast of northern Sumatra on 26 December 2004. The tsunami that was generated devastated coastal communities in Indonesia, Sri Lanka, India, Thailand and many other countries with waves ranging up to 30 m (100 ft)(Nalbant et. al, 2005). The tsunami struck south India and large scale devastation was reported. Tamilnadu was the "worst affected" with possibly over 8,000 people killed. At least 7,910 people were confirmed dead in Tamil Nadu with over 100 more people dead in Chennai alone. According to the Oxfam report, as many as four times more women than men were killed in some regions because they stayed at home caring after their children or were waiting on the coast for the fishermen relatives to return from offshore areas (BBC News, 2005). Chennai was worse hit by the tsunami and its entire Marina coastline was severely affected. According to government estimates, about 44,000 families in the Chennai District faced the direct impact of the destructive waves, loosing relatives, their livelihood and their properties. (Rao, 2005)

The inhabitants of Tamil Nadu's coastal areas had a variety of occupations which included many trades such as fishing, selling fish, domestic help, auto driving, peddlers and hawkers, painters, carpenters and other miscellaneous activities. Many of the women who lost their husbands and sons by the tsunami found themselves heading their remaining families. Thus, special attention was given to women who headed households, as they were no longer able to resume their traditional roles and hence they required specific support in preparing for new livelihoods and assignment of legal inheritor certificates.

1.2. Women and the Media

India is a large and diverse country with equally sizeable and varied media. The mainstream media does not merely “reflect” reality but shapes it, both at ideological and material levels. While at times the media is relatively open to the majority of women’s roles and their contribution, these attempts often remain unseen and unheard of because of much stronger forces of negative messages. However, since the women’s movement of the 1970’s and 1980’s, issues related to women began to be addressed and find their way into mainstream media (Janaki, 2006).

Many issues related to women’s struggles against violence, dowry, rape and their fight to protect the environment, have received a great deal of sympathetic coverage in newspapers and in television channels. Hence, the role of mass media is not just to import information on science and technology to the people but to have a desired impact upon their minds. This is only possible when the people that work for the media are fully aware of the life, attitudes and problems of the people in their communities (Joseph, 2005)

1.3. Need for the Study

The 2004 tsunami was not only disastrous in India but affected people worldwide. While looking deep into the problems related to the tsunami, it is tragic to note that even a natural disaster can be profoundly discriminatory. The majority of those killed were women and children. This entire proposition regarding the intense need to address women’s specific concerns arises by the fact that the tsunami killed more women than men. Women who survived the tsunami but were dislocated faced a numbers of problems. During the post-tsunami rehabilitation period, the various media covered widely such problems and the issues related to the consequences that had affected women’s communities. The nature of disaster created immense changes in the livelihood of women which affected them both economically and psychologically.

1.4. Aim

The purpose of the present study was to identify and evaluate the effectiveness of the media in communicating needed information in the rehabilitation of women that were impacted by the tsunami, and specifically in determining the role of media in helping improve the status of the women that were forced to migrate from Ernavour and Ennore of North Chennai.

1.5. Objectives

The study focused on the following objectives:

- Determining the knowledge and awareness of facts and information about tsunamis provided through the media to women’s groups.
- Analyzing the amount of exposure by the media in communicating effectively tsunami and natural disaster information to women.

- Analyzing the role of the media in public education and in providing solutions that help ed the rehabilitation of women affected by the tsunami.
- Determining media efforts in the overall rehabilitation of tsunami stricken areas.
- Analyze the impact of the media in the rehabilitation of women affected by the tsunami

2. REVIEW OF LITERATURE

Most of the studies conducted in India in the field of developmental communication focus on issues unrelated to gender. Very few efforts have been made to study the role of women in mediated development. However, the role of mass media in women's development has attracted the attention of social scientists. Gallagher has produced a most valuable document under UNESCO's sponsorship which clearly establishes that media has offered unequal opportunities to women (Ramanamma, 2005).

The private partners and the media networks were involved at all levels to ensure equal access for women in the area of information and communication technologies. Media would be encouraged to develop codes of conduct, professional guidelines and other self-regulatory mechanisms to remove gender stereotypes and promote balanced portrayal of women and men (Janaki, 2006).

Women in fishing communities are economically weaker than in other communities. Often, such groups suffer more from the direct consequences of a natural disaster because they are less informed, less prepared and less protected. Also, they suffer more from the indirect impact in private and public life as the disaster is transferred and compounded via economic, social, political and family relationships (Rosengren, 1985).

The special protection needs for women require careful consideration. The voices and perspectives of women and women's support networks need to be given visibility in national strategies for relief and reconstruction, by aid organizations and by the media. By responding in this fashion, a crisis can be turned into an opportunity for laying the foundations of a future where all people can live with dignity, security and justice (Ivan, 2005).

Gender is often seen as a narrow, special interest issue far removed from mainstream news coverage. However, gender awareness can actually lead to a better and more holistic understanding of any event and its after-effects. Taking the time and trouble to talk to women and women's groups - even in a crisis situation - can not only yield insights into the larger picture but point the way to special stories that are not only interesting but significant (Sharma, 1987).

The media and its professionals stand to gain by recognizing that during a disaster there is a gender dimension related to every event, process and institution. The information covered by the media originates from the individual experiences of those women - including poor and illiterate women – who have gained information, knowledge and opinions because of actual exposure to hardship (Devadas, 2005; Sharma, 2005).

There were a few scattered glimpses in media coverage soon after the disaster struck India of the special vulnerabilities of women in such situations. For example, there was one story about women having been hampered by their sarees in their bid to escape the waves. Another one was about women being raped and molested in unprotected refugee camps (Oxfam, 2005). Since mainstream media are the main channels in creating disaster awareness and disseminating information about programmes launched by the government for the welfare of the public, a proper understanding of the communication process is indispensable to introducing planned changes in a democratic society like India. In his essay "Designing Messages for Development Communication: An Audience Perception Based Approach" Bella (1991) has critically opposed the 'Dominant Paradigm' and argued for upward movement of communication and development based on active participation of the people.

Media coverage of humanitarian crises is widely believed to influence charitable giving, yet this assertion has received little empirical scrutiny. Using Internet donations after the 2004 tsunami as a case study, shows that the media coverage of disasters has a dramatic impact on donations to relief agencies, with an additional minute of nightly news coverage increasing donations by 0.036 standard deviations from the mean, or 13.2% of the average daily donation for the typical relief agency. Similarly, an additional 700-word story in the New York Times or Wall Street Journal raises donations by 18.2% of the daily average. These results are robust to controls for the timing of news coverage and tax considerations. The analysis using instrumental variables to account for endogeneity bias and the estimates are unchanged. However, it was founded that the effect of news coverage varies considerably by relief agency (Brown and Minty, 2004).

Mainstream media are useful if they promote mass participation as a means or an end. As we know that the tsunami killed more people in 12 countries spanning South-east Asia, South Asia, and East Africa while, according to the Red Cross, more than 1.6 million people were displaced. And yet there is precious little accurate, disaggregated data that shows how many of the dead were women, or how many women were missing or displaced. In Indonesia, four villages in the Aceh Besar district surveyed by Oxfam Community Aid Aboard (2005), shows that "four times as many women as men were killed" and only 189 of 676 survivors were female. Male survivors outnumbered female survivors by a ratio of almost 3:1. In four villages in North Aceh district, out of 366 deaths, 284 were females. Females accounted for 77 per cent of the deaths. In the worst affected village of Kuala Cangkoy, the ratio was 4:1.

Several criteria were used in assessing the impact of disaster media coverage on viewers. In his report Bandura (2006) notes, "Past correlated experiences heighten vicarious arousal because they make what happens to others predictive of what might happen to oneself"(emphasis added).

Communication is an important part of disaster prevention and management. An important channel is the mainstream media: Newspapers, television, radio and - increasingly important - the Internet. There were also hints of potential gender-related stories in some other early reports. Countless earlier examples of post-disaster and post-conflict situations, including the post-Kargil scenario, have demonstrated that the most vulnerable in society - including women and children - often tend to lose out in this process (Peters, 2005). Hawkey (2006) states: "We live on images and to grasp our humanity, we need to structure these images into metaphors and models." This sounds very much like what communication theorists have been saying about media image and metaphor as they relate to a story.

Media coverage on disaster issues were presented as text, as process and as mediator of reality. This theoretical development began with the study of media effects in early communication studies. An article entitled "Impacts of media coverage on the community stress level in Hong Kong after the Tsunami on 26 December 2004" (Lau, 2005), suggested a study of media coverage in terms of frequency of coverage, visual images and distressful contents as a strong predictor of stressful responses related to the tsunami. Another article entitled "Human misery is bigger news than a safe population" (Akkam, 2006), emphasized that the media has a significant role in lobbying for administrators to become more responsive and in bringing attention to the fact that the vulnerability of women to disasters depends on their social, cultural and economic status. Another article from the UN 2005 Chronicle entitled "Earthquake and Tsunami in the India Ocean", revealed that the Indian Ocean tsunami produced some very gender-specific impacts, ranging from women's traditional role in caring for the sick to increased cases of rape and abuse. Understanding and measuring these differences is essential for an effective post-disaster response and recovery.

3. METHODOLOGY

3.1. Survey Method

A comprehensive survey was carried out to determine the media role in helping rehabilitation problems of women victimized by the 2004 tsunami. The survey collected opinions and experiences directly from women impacted by the tsunami. The data was analyzed to establish the role of the media and its effectiveness in communicating tsunami issues to women. The survey covered various age groups of both illiterate and semi-literate women from those that migrated from Ernavour and Ennore to North Chennai.

3.2. Sampling

Chennai is the capital of Tamilnadu, one of the most important, densely populated and fast developing states in India. The survey was conducted randomly on North Chennai. Two hundred women were selected as a representative sample from the total population and the surveyors used individual questionnaire forms to collect and record views and opinions from the respondents. On the basis of this survey, a comparative analysis was done to find the lack of communication and awareness on tsunami rehabilitation issues among the tsunami affected women.

The questionnaire consisted of two parts. Part I dealt with the personal information of women, such as age, religion, education, marital status, family size, children, occupation and income before and after the tsunami struck. Part II contained questions pertaining to their media exposure in communicating tsunami information before and after the disaster struck.

3.3. Case Study

The present study is one of depth rather than breadth. It was essentially an intensive investigation with the objective of determining factors that could account for behavior-patterns of the given unit as an integrated totality. Thus, the study was undertaken to understand women's problems after the tsunami and to analyze media exposure in communicating the necessary information related to tsunami rehabilitation of the women adversely affected.

4. FINDINGS AND DISCUSSIONS

The following section provides the results of the survey and an analysis of the collected data.

4.1. Occupations before the tsunami

Table 1 summarizes accurately the occupations of the women in the surveyed group before the tsunami struck. Nearly 49% were daily wagers, 22% were housewives, 19% were small entrepreneurs, and 10% were employees.

Table 1. Occupations before tsunami

S.No	Occupation	No of Women	Percentage
1.	Housewives	47	22
2.	Small scale business Entrepreneurs	39	19
3.	Daily wage workers	102	49
4.	Employees	21	10

4.2. Occupations after the tsunami

Table 2 summarizes the occupations of the same women in the group after the tsunami struck. The survey shows that 52% were daily wagers, 23% were small business entrepreneurs, 14% were employees and 11% were housewives. Comparison of Table 1 and Table 2 clearly identified that after the tsunami the percentage of housewives decreased and more women had to go to work. This also illustrated graphically by Figure 4.1(a).

Table 2. Occupations after Tsunami

S. No	Occupation	No of Women	Percentage
1.	Housewives	25	11
2.	Small scale business Entrepreneurs	48	23
3.	Daily wage workers	109	52
4.	Employees	27	14

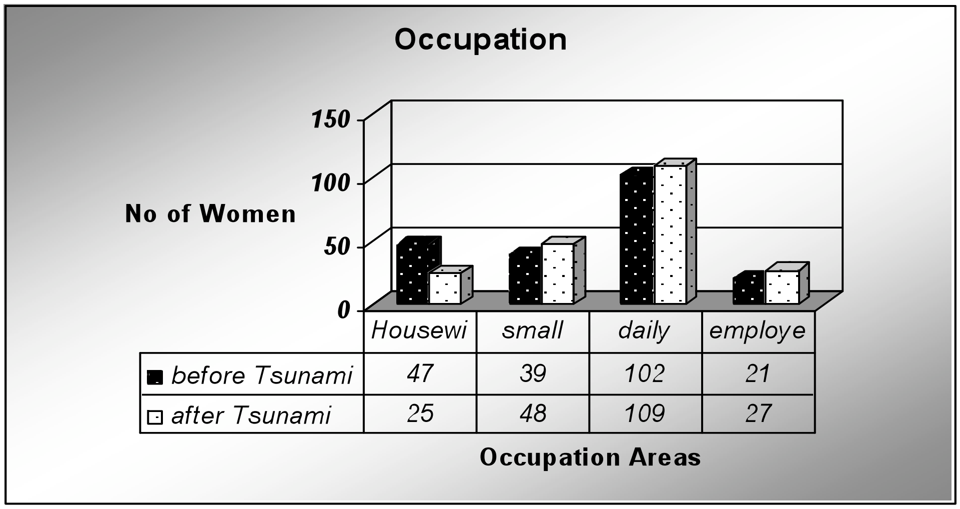

Figure 4.1(a). Occupational status of women respondents before and after Tsunami

4.3. Annual Income before the Tsunami

Table 3 provides data on the income distribution of the women in the group prior to the tsunami. The survey determined that 30% had annual income ranging up to Rs.10,000, while 20% had annual income ranging up to Rs.40,000. About 17% of those surveyed belonged to Rs.10,000 – Rs.20,000 group, 17% belonged to the Rs.20,000 – Rs.30,000 group and 16% belonged to the Rs.30,000-Rs.40,000 group. It became clearly evident from the survey that the majority of the women who had been victimized by the tsunami belonged to the lower income groups which did not have sufficient economic support from small scale business and daily wages.

Table 3. Annual Income before Tsunami

S.No	Income	No of Women	Percentage
1.	Upto 10,000	63	30
2.	10,000 to 20,000	36	17
3.	20,000 to 30,000	35	17
4.	30,000 to 40,000	33	16
5.	40,000 and above	42	20

4.4. Annual Income after the Tsunami

Table 4 reveals that up to 19% of the surveyed women belonged to Rs.10,000/- annual income group and 22% belonged to the Rs.40,000 group. About 14% belonged to Rs.10,000 – Rs.20,000 group, 25% in the Rs.20,000 – Rs.30,000 group and 20% in the Rs.30,000-Rs.40,000 group. This also confirmed that majority of women affected by the tsunami belonged to the lower income groups.

Table 4. Annual Income after Tsunami

S.No	Income	No of Women	Percentage
1.	Upto 10,000	39	19
2.	10,000 to 20,000	29	14
3.	20,000 to 30,000	52	25
4.	30,000 to 40,000	43	20
5.	40,000 and above	46	22

4.5. Family Size

Most of women affected by the tsunami were married. Usually, early marriages are more common in areas where illiteracy rate is higher. The survey indicated that the family size ranged between 3 to 5 members (Table 5), but about 15% had six members in their family.

Table 5. Family size

S.No	Income	No of Women	Percentage
1.	2 members	14	7
2.	3 members	25	12
3.	4 members	93	44
4.	5 members	45	22
5.	6 members	32	15

4.6. Mass media preference before tsunami

In regard to the mass media preference, Table 6 indicates that more than half i.e., 59% of women affected by the tsunami preferred television because it is the most powerful medium of mass communications in the electronic age, since it provides visual as well as technical background information. Whereas 16% of the more literate women preferred newspapers, 19% stated that radio was their preferred media and 6% stated showed magazines because of the easy of accessibility.

Table 6. Mass Media preference before the tsunami

S.No	Medium	No of Women	Percentage
1.	Newspapers	34	16
2.	Magazines	12	6
3.	Radio	39	19
4.	Television	124	59

4.7. Mass media preference after tsunami

In regard to preference of mainstream media after the tsunami, the survey data in Table 7 shows that 61% of the women affected by the tsunami preferred television because it is the most powerful medium of mass communication - which also helps create opinions and perceptions. Television broadcasts specifically emphasized information messages related to tsunami rehabilitation. Also, the survey determined that 10% of the respondents in the group preferred newspapers, 24% preferred radio and 5% preferred magazines. Comparison of Tables 6 and 7 - graphically illustrated by figure 4.7 - clearly indicate that more than half of the women respondents preferred television and that there was an increase in preference by 4% after the tsunami. The data indicates strong public support of all media resources during the tsunami disaster. The variation in the preferences is mainly due to the availability and accessibility of certain media and also in difference of understanding the messages. Thus, the mainstream media – and particularly television - played a significant role in communicating information to the tsunami affected women which helped with their efforts of rehabilitation and further development after the disaster.

Table 7. Mass media preference after the tsunami

S.No	Medium	No of Women	Percentage
1.	Newspapers	24	10
2.	Magazines	09	5
3.	Radio	49	24
4.	Television	127	61

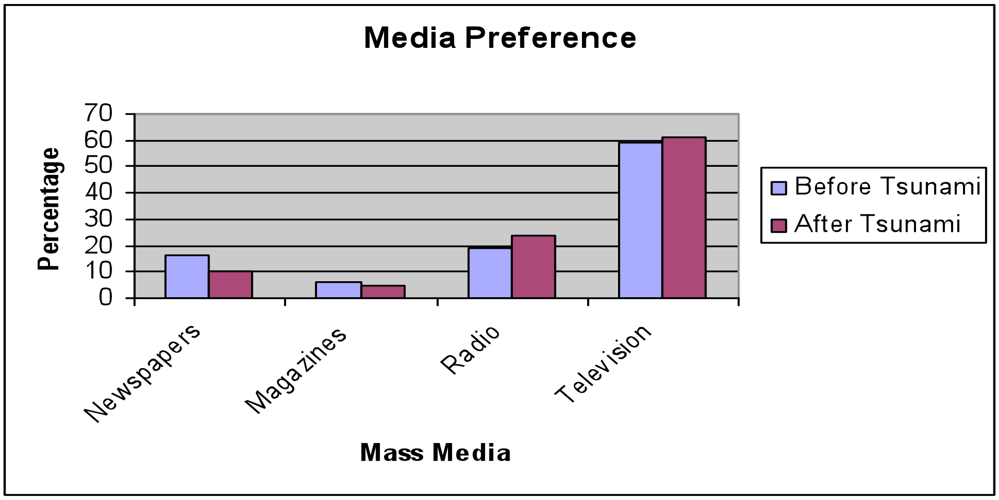

Figure 4.7 – Media Preference of Women affected by the Tsunami

4.8. Help rendered by different media to Respondents

Table 8 summarizes the results of the survey as to which of the media provided information that was most helpful to the women affected by the tsunami. Again, 61% of the women respondents identified television, 10% identified newspapers, 24% identified radio and 5% identified magazines. Overall, it was clear that the mass media plays a significant role in communicating useful information. In fact, because of their exposure to the media many of the respondents in the survey got job opportunities or gained other economic help from the government and NGOs.

Table 8. Help rendered by different media to the respondents

S. No	Most helpful Medium	No of Women	Percentage
1.	Newspapers	23	10
2.	Magazines	07	5
3.	Radio	51	24
4.	Television	128	61

4.9. Most of the supportive Programmes in Television media

From the above data, it becomes clear that television played a major role in communicating information for tsunami rehabilitation. 83% of the respondents stated that news bulletins were particularly helpful during and after the tsunami struck by updating needed information (Table 9). Also, it became clear that news bulletins were the most helpful programs in helping the women affected by the 2004 tsunami. The national television channel “Doordharsan” telecasted a special programme about tsunami rehabilitation – as pointed out by most of the women respondents. However, 12% mentioned that special interviews in certain local regional channels communicated effectively tsunami-related issues, 7% mentioned special programs and 2% mentioned documentary material by a few local channels. In some cases it appeared that language difficulties among the respondents may have been a barrier for effective communication by the media.

In conclusion, mass media plays a significant role in the perception of modernization and helps significantly by including Job opportunity messages. In fact, because of exposure to the media many respondents got jobs or other economic help from Government and NGOs.

Table 9. Most of the supportive programmes of television media

S.No	Most helpful Programmes	No of Women	Percentage
1.	News Builtins	173	83
2.	Special Interviews	25	12
3.	Special Programmes	7	3
4.	Documentaries	4	2

4.10. Case Study

As previously stated the study involved a comprehensive survey of women affected by the 2004 tsunami in north Chennai. The study required an intensive investigation, careful observations and analysis of women's rehabilitation issues, as well as the women's knowledge and awareness of media communications, of their family backgrounds, of lifestyles, of psychological behaviors and of their economic status before and after the disaster. Also, the study was undertaken in order to better understand women's problems after the tsunami and to analyze and evaluate the media exposure in communicating necessary information related to their rehabilitation. This is one of the pioneering studies that attempts to find out the perspectives of mediated developmental communication as focused on and understood by the tsunami affected women in North Chennai. It has also focused on the relationship between media and women in the development context of North Chennai.

The tsunami affected people in Ernavour and Ennore were forced to migrate to North Chennai because of lack of basic necessities at home where the impact of the disaster had been severe. Nearly, 75 percent of the people in these areas depended on fishing for their livelihood. Furthermore, their socio-economic conditions were generally low along with a very low literacy rate. Most people – even the young – were semi-literates. The delay in permanent rehabilitation for many of the tsunami victims in the state led to loss of livelihood and resulted in serious socio-economic problems – some even selling their kidneys to make living. The share autos were doing a brisk business moving people to collect relief material - cooking utensils and plastic pots – provided by Karunalaya, an NGO in Tondiarpet, Chennai. Indian women traditional wear sarees and blankets which were tied to poles to serve as makeshift shelters for the residents (The Hindu, 21/06/2005).

In addressing the problem of the people in the tsunami affected areas, Government and NGOs like Karunalaya constructed semi permanent houses in Kathivakkam and Ernavour of Shennai. Because of tsunami safety considerations the semi permanent houses were constructed inland and at great distance from the coast where most people worked.

In official meetings with government officials, NGOs pointed out the difficulties of the affected people by stating that over a period of 10 months, they were forced to return to their original place even though it was nearer to the sea (The Hindu, 9/8/2005). Malathi, a 36-year old woman who lost her husband and children to the tsunami stated that the semi-permanent houses that were hurriedly constructed were not sufficed to live because there was no water, drainage and air circulation. The issue was covered by the media in order to bring the problems to the attention of the government, of the NGPs and of the general public, so that the steps could be taken to reconstruct better houses.

Another problem was the location of schoolswhich were spread across Kasimedu, Kalmandapam, Thiruvottiyur and Toll Gate, quite far from Ernavour. NGOs sponsored daily bus transportation for about 100 children to school (The New Indian Express, 07/06/2007).

Kanaga, a 17-year old commented that they received permanent houses three years after the tsunami and that houses were built small in one particular area, which characterized them as the tsunami affected people in the community. The government allotted 991 permanent houses in Tondiarpet in Chennai for tsunami victims - conveniently located near hospitals, government schools; a police station, the railway station, a bus stand and a market. Mainly this issue was covered as news by television stations and newspapers.

In summary, the tsunami had created chaos and confusion in the minds of the people in the region that was struck. Many of the women had lost husband, children, parents, brothers and sisters. Since they had lost the people on whom they were dependent, they now had to take care of raising single handedly their children and planning for the future. Women were forced to work in all kinds of trades to make ends meet. Some begun selling fish, flowers, vegetables, fruits or worked as house maids. Others did cleaning work at hospitals, worked as masons, managed marriage halls, did construction work, worked for export companies or ice companies. Still others begun work in animal husbandry or as clerks in all kinds of shops selling a variety of things.

Community teachers worked for a non-government organization "Karunalaya", a social service organization, working with slum children. At Tondaiyarpet, the organization performed welfare work for the people that had been affected by the tsunami. Also the teachers helped the media people to assess accurately the status of the affected women – work for which they were commended by the government of Tamilnadu. Community teachers working for NGOs stated that, due to lack of proper job opportunities, nearly ten women were forced to become sex workers and others became gamblers or engaged in illegal activities. Such behaviors created stresses among the affected women in the community. Community teachers stated that since the tsunami of 2004, there was an increase in teen marriages, in alcohol use and in women going into the sex trade.

The issue of child marriage after the tsunami became the to focus of media only in August 2007 (The Hindu, 2007). According to Rita, a community teacher from Karunalaya, the girls were married off early because their parents were without work and believed that their teenage daughters were "safer" in an early marriage, rather than in staying alone at home. According to teachers such incidents rose after the sudden 2004 disaster because the communities were experiencing a high degree of insecurity. Mental depression led numerous women into an increase use of alcohol. Some women were forced to sell their kidneys to pay for the high debt or to make a living. This issue was also given attention and discussed by the various media. Ms. Thilakavathy, a woman in her mid-30s with three young children was quoted as having her kidney sold for Rs.40,000. After her photo was published in newspapers and television she got some amount of money from an NGO. That amount was helpful to keep a shop of her own and to continue to support her children. Apparently the media, by focusing on such predicaments, was able to help suffering people and get them help.

The present in-depth study determined that many girls younger than 18, were forced to drop out of high school and get married. Others got menial jobs for a short period, then got married. The life that they started at such young age created many economical and psychological problems in their families. These issues were also covered by various newspapers and television channels and were brought to the attention of communities, suggesting solution for the affected women. Based on such reporting by the media, the government and the NGOs acted more effectively in instituting changes for post-disaster rehabilitation. Similarly, by repeated media commentary about the predicaments of the women affected by the tsunami, the government of Tamilnadu undertook necessary steps to provide housing for suffering families (The Hindu, 09.08.2005).

The above study represents only a qualitative analysis of the role the media played in improving the status of tsunami affected women through rehabilitation. Both the print and the electronic media played a major role in communicating significant information to government officials to the women impacted by the 2004 tsunami disaster and to the general public.

4.11. Results

According to the findings the following results were obtained.

1. With regard to the mass media preference, more than half of the women affected by the tsunami opted for television because it is the most powerful medium in communicating information for tsunami disaster rehabilitation.

2. The news features in television was most helpful. Nearly 83% of the responders to the survey stated that the facts and announcements on availability of resources helped them track some emergency information about the tsunami and about the rehabilitation problems.

3. From the analysis it was determined that early marriage for women (under age 18) increased after the tsunami and that coverage by the media brought attention to welfare committees and to the government to proscribe such early marriages.

4. The violence against women and the sexual harassments they suffered after tsunami was reported by the media, but the issues were not adequately focused to help resolve them.

5. Teen marriages, prostitution and alcohol use among women increased in north Chennai since the tsunami of 2004 and such problems have been widely publicized by various print media.

6. Problems, like poor hygiene and sanitation due to insufficient facilities, were pointed out by media to create awareness on needed improvements on public health.

7. Media presentations helped to educate the affected women about the tsunami risk factors and on the need for improved awareness and compliance to tsunami warnings.

8. The television and the print media reported on scientific and technical information about tsunamis, on post-disaster rehabilitation and on the need to find solutions that would benefit the general public as well as the women who had been adversely affected.

9. Present information about the impact of tsunamis and the safety of buildings and of areas have not yet been properly addressed. Currently available tsunami inundation maps are not appropriate for code or guideline applications. While rebuilding Ennore, the need for taking tsunami-related precautions must be emphasized and promoted by the media.

10. There is lack of livelihoods opportunities for women in the Ennore region in fisheries related

occupations and agricultural reclamation of saline lands. The media can play a vital role in motivating the affected women in the region to receive training in new skills that will help them improve their livelihood – and also bring to the attention of the government this need to provide training.

5. CONCLUSIONS

During and after the 2004 tsunami disaster, the media provided support to the affected people and contributed vital information for disaster relief and amelioration. Before and especially after the disaster, the media's role and responsibilities expanded in many and various ways in helping women by communicating to them essential information pertaining to the tsunami hazard. Also, by providing good coverage of issues and of specific problems, the mainstream media influenced government and non-governmental organizations to act promptly to help improve the economic status of women that had been victimized by the tsunami. As a result of media help and financial government support these women were able to cope with the hardships, improve their lives, enjoy closer family relationships and a higher degree of gender freedom. Thus, the mainstream media played a significant role in this process. However, in spite of such positive developments, there is still room for improvements that policy-makers must act upon to improve further the conditions for groups of women victimized by the tsunami disaster. For example, the creation of the fast tracked Self Help Groups (SHGs) and the manipulation in membership in different groups and their accommodation in temporary shelters must be better addressed and acted upon. The media revealed that such shortcomings still exist but so there is hope that policy-level changes will be made to correct the inequities and improve conditions for the victimized women.

In conclusion the media - with its reach and power - played a very important role in improving the life styles of affected women after the tsunami. However, the progress in media communications should not be limited to disaster periods only but should be expanded to help improve preparedness for future events that may occur. Sustainable society development with emphasis on safety from disasters, should be an extensive and substantial process hat needs to be continuously supported by the mainstream media.

5.1. Suggestions

1. The media should report on women's mental health - which is an essential factor for better livelihood.
2. Protection issues related to women – particularly the younger ones - should be given special attention. Perspectives and opinions of women and of their support networks need to be given greater visibility by the media in broadcasts related to national strategies for relief and reconstruction.
3. Issues pertaining to food security, health care and the needs of women and children must be addressed adequately by the media.

REFERENCES

I. Books:

1. Lorca et. al (1997). Earthquakes and Tsunamis.
2. Nalbant et al.(2005), Seismology: Earthquake risk on the Sunda trench, Nature. Vol. 435, No. 7043, P 756–757.
3. Janaki D (2006), "Tsunami and Women – Restructuring Family and Community", Mother Teresa Women's University Press, Kodaikanal, p 174 - 175, p 196.
4. Ramanamma M V (2005), "Media and Women Development", Anmol Publications Pvt. Ltd, New Delhi, p 45.
5. Rosengren (1985) Media Gratifications Research: - Current Perspectives, Beverly Hills: Sage Publications, p 77.
6. Ivan (2006), http://www.chmi.cz/katastrofy/media.html
7. Sharma K (2005), "Gendered Tsunami", http://www.thehindu.com/thehindu/mag/2005/04/03/stories/2005040300320300.html, Accessed date: 13.02.2005
8. Sharma S C (1987), "Media Communication and Development", Jaipur, Rawat Publication, p 15.
9. Oxfam Briefing Note (2005), "The Tsunami's impact on women", http://www.oxfam.org.uk/what_we_do/issues/conflict_disasters/bn_tsunamiwomen.html Accessed Date: 05.04.2006
10. Bella M (1991), "Designing Messages for Development Communication" , p 132
11. Oxfam Community Aid Aboard (2005), "Tsunami: report shows four times as many women as men killed", http://www.oxfam.org.au/media/article.php?id=11, Run Date: 26.03.2005, Accessed Date: 07.04.2005
12. Peters H P (2005), http://www.chmi.cz/katastrofy/peters.html
13. Hawkey(2006), http://www.waccglobal.org/wacc/publications/media_action/archive/232_feb_2001/media_in_disasters_a_disaster_in_media
14. Lau et al. (2005), "Impacts of media coverage on the community stress level in Hong Kong after the Tsunami on 26 December 2004", Center for Epidemiology and Biostatistics, School of Public Health, Faculty of Medicine, The Chinese University of Hong Kong
15. Ahuja R (1973), "Female Education in India, in Indian Journal of Social Work", p 58
16. Desai M K (1987), "women and society in India", Ajanta Books International, New Delhi, p 12
17. Choudhary R K (2005), "Research method in Mass Communication", Pearl Books, New Delhi, p 12
18. Rao P V (2005), "Scientific Background on Indian Ocean Earthquake and Tsunami", Indian Ocean Survey, Volume: 1, p 8.
19. Rajagopalan D (2006), "Tsunami and aftermath. A case study of Nagapatinam Village,Tamilnadu", M.Phil Thesis, Department of Anthropology, University of Madras, Chennai-600005

20. Brown P and Minty J (2004) http://www.wdi.umich.edu/files/Publications/WorkingPapers/wp855.pdf
21. Akkam A (2006), “Tsunami triggers changes in Tamil Nadu women’s lives”, http://www.eni.ch/articles/display.shtml?05-0433, Run Date: 09.06.2005, Accessed Date: 09.03.2006
22. Joseph A (2005), “Gender, media and Tsunamis”, http://www.indiatogether.org/2005/feb/ajo-genmedia.htm, Run Date: 02.02.2005, Accessed Date: 10.03.06
23. Devadas D (2005), “Tsunami crisis: Abandoned widows – India”, http://www.careaustralia.org.au/tsunami_story.asp?id=18, Run Date: 27.01.2005, Accessed Date: 03.04.06
24. Kandaswamy D (2006), “Media Forgets Female Face of Tsunami”, weNews , http://www.womensnews.org/article.cfm/dyn/aid/2390/context/archive, Run Date: 27/07/05 Accessed Date: 07/04/2006
25. National Commission for Women and Tamil Nadu State Commission for Women(2006), “Recommendations for Tsunami Victims”, http://www.disasterwatch.net/women_tsunami%20links/NCW%20recommendations.htm,
26. North Tamilnadu Tsunami Relief & Rehabilitation Committee (2006), “Concerns on Women & Children on Relief & Rehabilitation” (http://www.tsunami-india.org).
27. Rehabilitation of Women Victims of Tsunami (2006), http://www.tsunami2004-india.org/modules/sections/index.php?op=viewarticle&artid=44, Accessed Date: 03.04.2006
28. The Hindu (2005), “Kids ‘Parliament’ ticks off media over Tsunami coverage”, http://www.hinduonnet/2005/02/13/stories/2005021312260300.htm, Run Date: 12.02.2006, Accessed Date: 03.04.2006
29. The Hindu (2005), “Tsunami victims were not evicted: Government counter”, http://www.thehindu.com/2005/02/22/stories/2005022213480600.htm, Run Date: 21.02.2005, Accessed Date: 04.04.2006
30. Times of India (2006), “Livelihood rehabilitation scheme launched”, http://www.timesofindia.indiatimes.com/articleshow/1010563.cms, Accessed Date: 10.30.06
31. The Week (2005), “Woe-men of Tsunami”, by Litta Jacob/ Nagapattinam, The week, April 3, 2005
32. UN Chronicle (2005), “Earthquake and Tsunami in the India Ocean”, United Nation Department of Public Information, Outreach Division, Volume XLII, Number 1, March – May 2005
33. Roy, Prodipto, ET. Al (1969) “The impact of communication on Rural development”, National Institute of Community Development, Hyderabad.
34. Deccan Chronicle (13/01/2007), “Tsunami – hit sell Kidneys”, p 1.
35. Dinamalar (14/01/2007), “Sirunika mosati”, p 1
36. Dinakaran (26/12/2006), “kidney rocket”, p 1
37. Malai Malar (15/07/2005), “Ernavour-l tsunami paditha makkalugu 2500 veetukal”, p 1
38. The Hindu (30/05/2005), “10,000 tenements for tsunami victims soon”, p 4
39. The Hindu (20/08/2007), “Media’s role in covering natural disasters debated”, p 4
40. The Hindu (09.08.2005), “Tsunami relief: Central officials meet NGOs”, p 4
41. The New Indian Express (02/06/2005),” Boat manufacturers chip in with price cut”, City Express, p 2.

42. The New Indian Express (31/05/2005), “with boats, hope floats for these fisher folk”, City Express, p 2.
43. The New Indian Express (28/05/2005), “Mobile shops distributed among fisher women”, p 5.
44. Sujatha R (2007 July 17), “Teen marriages on the rise since the Tsunami”, R. Sujatha, The Hindu, Dated: 17.07.2007, p 4

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TSUNAMIGENIC SOURCE MECHANISM AND EFFICIENCY OF THE MARCH 11, 2011 SANRIKU EARTHQUAKE IN JAPAN

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ABSTRACT

The great Tohoku earthquake of March 11, 2011 generated a very destructive and anomalously high tsunami. To understand its source mechanism, an examination was undertaken of the seismotectonics of the region and of the earthquake' focal mechanism, energy release, rupture patterns and spatial and temporal sequencing and clustering of major aftershocks. It was determined that the great tsunami resulted from a combination of crustal deformations of the ocean floor due to up-thrust tectonic motions, augmented by additional uplift due to the quake's slow and long rupturing process, as well as to large coseismic lateral movements which compressed and deformed the compacted sediments along the accretionary prism of the overriding plane. The deformation occurred randomly and non-uniformly along parallel normal faults and along oblique, en-echelon faults to the earthquake's overall rupture direction – the latter failing in a sequential bookshelf manner with variable slip angles. As the 1992 Nicaragua and the 2004 Sumatra earthquakes demonstrated, such bookshelf failures of sedimentary layers could contribute to anomalously high tsunamis. As with the 1896 tsunami, additional ocean floor deformation and uplift of the sediments was responsible for the higher waves generated by the 2011 earthquake. The efficiency of tsunami generation was greater along the shallow eastern segment of the fault off the Miyagi Prefecture where most of the energy release of the earthquake and the deformations occurred, while the segment off the Ibaraki Prefecture – where the rupture process was rapid – released less seismic energy, resulted in less compaction and deformation of sedimentary layers and thus to a tsunami of lesser offshore height. The greater tsunamigenic efficiency of the 2011 earthquake and high degree of the tsunami's destructiveness along Honshu's coastlines resulted from vertical crustal displacements of more than 10 meters due to up-thrust faulting and from lateral compression and folding of sedimentary layers in an east-southeast direction which contributed additional uplift estimated about 7 meters - mainly along the leading segment of the accretionary prism of the overriding tectonic plate.

Keywords - *Japan; Honshu; Sanriku; earthquake; seismotectonics; tsunami; source-mechanism; tsunamigenic efficiency; Japan Trench.*

I. INTRODUCTION

The most powerful earthquake in Japan in recent years occurred on March 11, 2011 off the coast of Sanriku (which includes the Aomori, Iwate, and Miyagi prefectures) (Fig. 1). It was one of five great earthquakes in the world since 1900. It generated a Pacific-wide, tsunami, which was particularly devastating and anomalously high along the northeast coast of Honshu. Warnings were issued for more than 20 countries and Pacific islands.

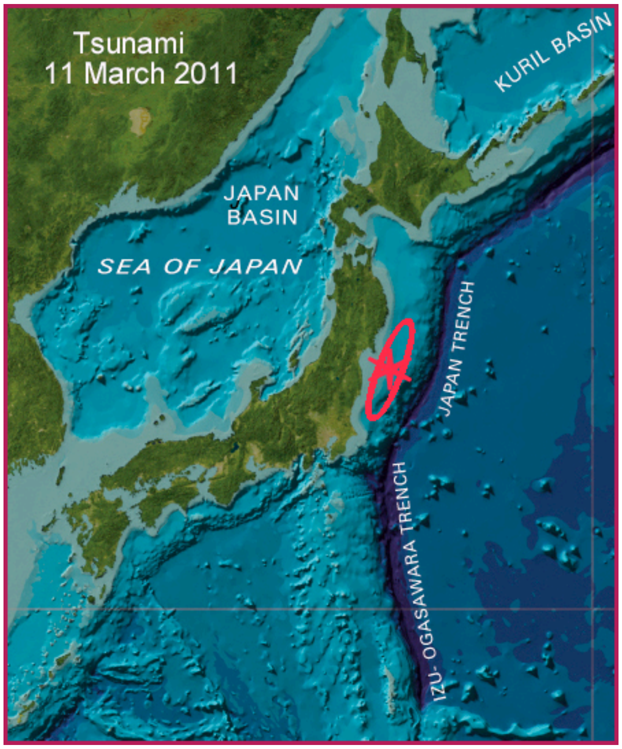

Fig. 1. Epicenter of the March 11, 2011 Earthquake; Tsunami Generating Area; Major Basins and Trenches

In Japan, both the earthquake and the tsunami caused extensive and severe damage to roads and railways, ignited fires and triggered a dam collapse. Many electrical generators were taken down. Most of the destruction and deaths in Japan were caused by the tsunami. As of April 18, 2011 the death toll in Japan had risen to 13,843, another 14,030 people remained missing and another 136,481 were displaced (Japan's National Police Agency). The disaster left about 4.4 million homes in northeastern Japan without electricity and 1.4 million without water. There were power outages for about 4 million homes in Tokyo and the surrounding areas. Early estimates indicated that the monetary losses would exceed $100 billion.

To understand the tsunami's generation mechanism and the cause of the extreme wave heights along northeast Honshu, an investigation was undertaken of the seismotectonics of the region and of the earthquake's focal mechanism, rupture patterns and spatial and temporal sequencing and clustering of major aftershocks – the latter defining the limits of crustal displacements and the amount of energy release. Evaluation of the tsunamigenic efficiency includes a review of the combined earthquake rupturing impact on both the subducting oceanic lithosphere and on the overriding plate, as well as examination of other large vertical and lateral displacements that contributed to the tsunami's anomalous height. Additionally evaluated are the temporal elastic deformations caused by faulting and the collateral impact of lateral compression on the sediments on the accretionary wedge near the trench axis. Finally, the 2011 tsunami source mechanism is compared with those of previous destructive events in 1896 and 1933 for the purpose of evaluating similarities of factors that contributed to the enhancement of the tsunami's height and destructiveness.

2. THE EARTHQUAKE AND THE TSUNAMI

2.1 The Earthquake

The March 11, 2011 earthquake occurred at 05:46 UTC, 14:46 JST (local time). The quake epicenter was at 37.68N; 143.03E (USGS) was about 373 kilometers (231 miles) away from Tokyo, about 130 kms (81 mi) off the east coast of Oshika Peninsula and about 150 km west of the tectonic boundary of the Eurasian and Pacific plates, characterized by the Japan Trench (Fig. 1). Strong ground motions were felt as far away as Tokyo. The Moment Magnitude was initially estimated at Mw=8.9 (USGS) but later revised upward to Mw=9.0. However, based on long period surface waves (ranging from 166 to 333 seconds), the total seismic moment was recalculated to be about 5.6x10^22 Nm, corresponding to a moment magnitude of 9.1 - almost as much as that of the 2004 Sumatra earthquake (Mw 9.15). The focal depth was 15.2 miles (24.4 kms) (USGS). Focal mechanism analysis indicated a low angle nodal plane with a strike of 199^0, a dip angle of 10^0 and a slip angle of 92^0 (Shao et al., 2011).

2.2 The Tsunami

2.2.1 Near and Far Field Tsunami Impact

The near and far field effects of the tsunami and the quantitative runup heights have been reported in the literature and in preliminary Internet summaries (Pararas-Carayannis, 2011).

Near-Field Effects - Waves began striking the shores of Sanriku a few minutes after the quake. The impact was particularly devastating along coastal areas of northeastern coastal areas of Honshu, where the irregular coastline and numerous bays amplified the tsunami height and its destructiveness.

Hardest hit was the Miyagi Prefecture (Fig. 2). In some areas the waves inundated as far as 10 kms (6 miles) inland. Further south, at the Fukushima Daiichi Nuclear Power Plant, a 19-foot high protective levee was overtopped by the tsunami, which submerged the lower height structures including the diesel generators and knocked out regular and backup cooling systems. The maximum tsunami wave height was ~46 feet. A 150-foot high splash was photographed as the tsunami impacted the turbine building of the plant, passing over its roof and striking the adjacent reactor building. Four of the plant's six reactors suffered damage to their radioactive cores. A state of emergency was declared which required massive evacuation of more than 200,000 residents living within a 20 km (12 mi) radius.

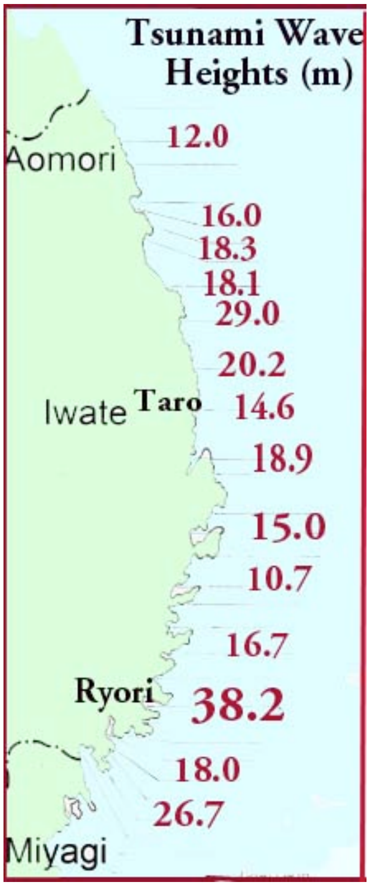

Fig. 2 Reported Maximum Tsunami Heights in meters along the Sanriku coast.

Reported run-up heights ranged up to 25.5m, but at Koborinai the maximum runup reached 37.9 meters (124 feet). A fire was ignited at an oil refinery in Chiba Prefecture near Tokyo. At Rikuzentakata the maximum tsunami wave was 13 meters high and overtopped the existing protective tsunami seawall, which was 6.5 meters high. The tsunami reshaped the entire coastline and flooded the agricultural fields further north. Along the Taru District the tsunami overtopped the protective seawall and caused extreme destruction. Reported run-up heights ranged form 19.5m to 25.5m. At Ryori Bay-Shirahama, the tsunami run-up height reached 23.60 meters. At the fishing village of Ryoishi the waves destroyed part of the 9-meter (30-foot) protective tsunami wall or simply overtopped it completely destroying everything in the way. At Iwate, the GPS ocean gauge located in 204 meters depth in the offshore area measured a 6.7 meters (22 ft) tsunami height. At Miyako, waves of 11.5 meter overtopped the existing tsunami barrier and seawall, which was 7.6 meters high. The tide gauge recorded a tsunami height of 8.5 meters. However, run-up heights of as much as 19.5 and 25.5 meters were reported from this area.

At Natori, the tsunami height was 12 meter near Sendai airport and 9 meters high near the fishing port. At Kesennuma, the wave heights ranged from 9.10 to 14.7 meters. At Kamaishi, the waves ranged from 7-9 meters in height. The maximum tsunami height at Ofunato was 8.0 meters and at Arahama 9.3 meters. At Ishinomaki, the tsunami was 5 meter high in the harbor but runup reached 16 meters at Ogachi-machi. At Kashima Port, 4.22 meter and 5.2 meter tsunami heights were observed. At Fudai, 3,000 residents survived because of a 51-foot (15.5 meter) floodgate. However, the tsunami run-up at the towers of the floodgate reached 66 feet (20 meters). At Ishinomaki City the tsunami was over 10 feet high and washed homes away.

Far-Field Effects **–** The tsunami's energy flux radiated across the Pacific and caused extensive destruction at distant shores in the Hawaiian Islands, California, Oregon, Chile and elsewhere (Fig. 3). Figure 2 provides the tsunami travel times and the location of DART and of coastal tide stations.

Vanuatu - The tide gauge measured 1.88 meters (6.2 feet).

Hawaiian Islands – Maximum runup heights ranged from 2 to 3 meters (7 to 11 feet) on the islands of Maui and Hawaii (the Big Island). Four waves struck Midway Atoll at the Northwest end of the Hawaiian Islands. The highest wave reached a height of nearly 5 feet and completely washed out the reef and Spit Island, the smallest in the atoll. The tide gauge measured 1.27 meters (4.2 feet). According to reports the tsunami killed hundreds of birds and swept away nests protecting seabird chicks, which were unable to fly. Reportedly, 110,000 Layson and black-footed albatross chicks were killed, along with 2,000 adult birds.

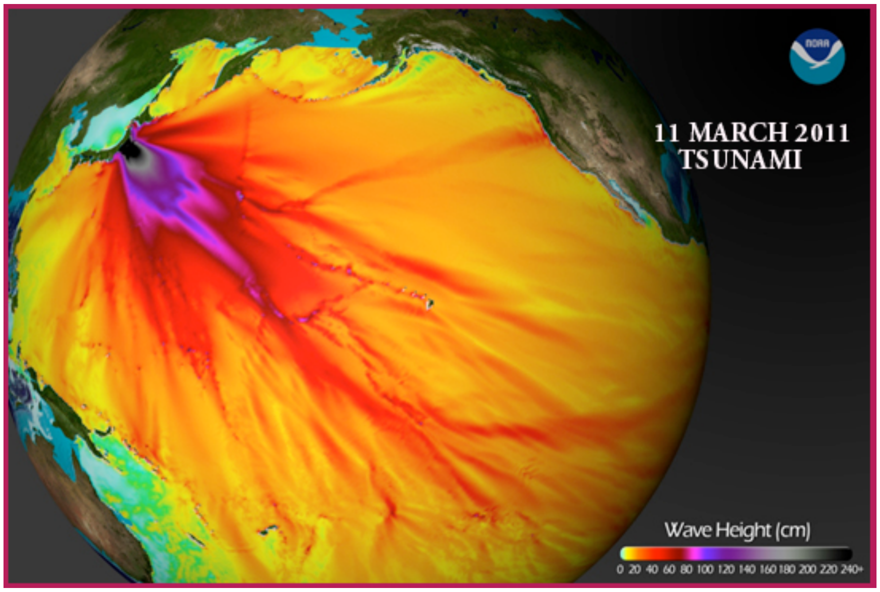

Fig.3. Tsunami Energy Propagation Across the Pacific (NOAA graphic).

Damage to boats on the island of Oahu was extensive. Kahului on the Island of Maui suffered the worst damage. The tide gauge there measured 1.74 meters (5.7 feet). On the Island of Hawaii, there was flooding and minimal damage of a hotel lobby near Kealakekua Bay. The Hilo tide gauge measured a 0.69 meters (2.3 feet) high wave.

California - There was damage to docks and boats. At Crescent City, tsunami waves did extensive damage to port docks and severely damaged 35 boats. The reported maximum wave height was estimated at 2.5 meters. The tide gauge measured a wave of 2.02 meters (6.6 feet) high. The tsunami caused also extensive damage at Santa Cruz Harbor, estimated at more than 2 million dollars.

Oregon - Wave heights were relatively small, ranging from .90 and 1.20 (3 to 4 feet). Wave periods ranged from 10-15 minutes.

Chile – There were reports of major damage. Maximum-recorded tsunami runup at Coquimbo was 2.55 meters, at Caldera 2.43 meters and at Talcahuano 2.15 meters.

3. SEISMOTECTONICS OF THE REGION

Active tectonic convergence of the Pacific plate with the Eurasian and North American plates has created an extensive and complex tectonic plate margin along the Japanese island group. The following is a brief overview of the seismotectonics of the region.

3.1 Tectonic Evolution

Japan was originally the coastal part of Eastern Eurasia. However, many hundreds of millions of years ago (from mid-Silurian to the Pleistocene) oceanic crust movements caused by subduction processes began pulling Japan away from the continental block. About 15 million years ago these processes begun to open the Sea of Japan - a complex basin between Japan and the Korea/Okhotsk Sea Basin - which represents another sub plate with apparent counter clock rotational movement as it interacts against the Okhotsk plate along the inland sea boundary of the Hidaka Collision Zone (HCZ) (Fig. 4).

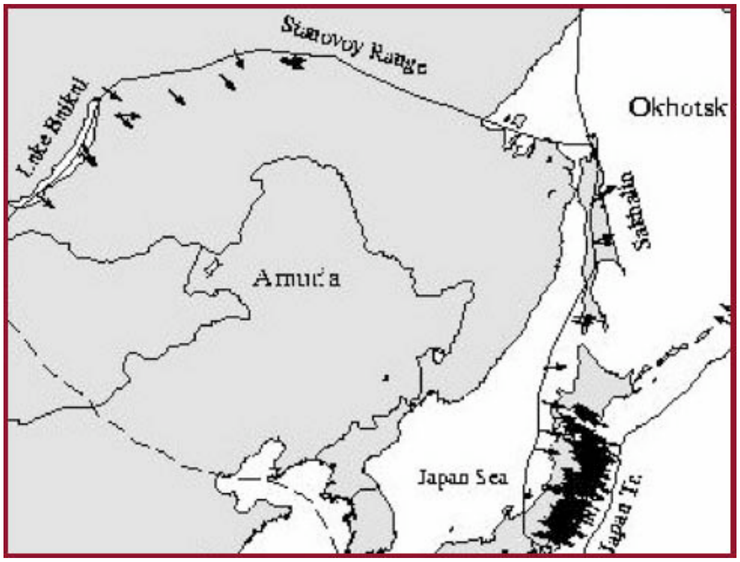

Fig. 4. The postulated Amurian Microplate (Modified after Wei and Seno, 1998)

Thus, a separate Amurian microplate has been postulated (Wei and Seno, 1998). Two earthquakes in 1983 and 1993 in the eastern boundary of this microplate generated destructive tsunamis in the Sea of Japan basin. Furthermore, Sakhalin Island, north of Hokkaido, which separates the Sea of Japan from the Sea of Okhotsk, is probably the result of transpressional tectonics along the North America-Eurasia boundary (Pararas-Carayannis, 1983,1994). However, whether the Okhotsk plate and Northern Honshu is part of the North American plate or not, has not been ascertained (Seno et al., 1981). Similarly, whether Honshu is part of the North America plate, of the Eurasian plate or an independent microplate has not been determined.

In brief, Japan is a mature island arc. Subduction of the Philippine Sea Plate beneath the continental Amurian Plate, the Okinawa Plate to the south and of the Pacific Plate under the Okhotsk Plate to the north, continues to the present day and is the cause of frequent earthquakes, tsunamis and of occasional volcanic eruptions. The convergence rate across the boundary between the Pacific and Eurasian tectonic plates along the east side of Honshu Island varies from about 8 to 9 cm/year (3.1 to 3.5 in). As the Pacific plate subducts under Honshu, the high convergence results in the build-up of stresses. Arc stresses contribute to back-arc spreading (Seno & Yamanaka, 1998). After reaching aseismically a threshold of elastic deformation, the stresses are suddenly released by earthquakes. Large tsunamigenic earthquakes occur periodically near the eastern tectonic boundary characterized by the Japan Trench as the western edge of the Pacific Plate subducts under Honshu. Destructive tsunamis are generated from large earthquakes either on the outer ridge of the subducting plate or on the overriding plate, west of the Japan Trench – where the extensive forearc and accretionary sedimentary wedge seem to have significant effects on the type of boundary slips that can be expected and on the frequency and intensity of tsunami-earthquakes.

3.2 Seismicity of Japan

Japan accounts for about 20 per cent of the world's earthquakes. Its high seismicity (Fig. 5) results from compression along the Pacific-North America subduction zone, from outer rise and intra-plate events and from magmatic effects of plumes or super plumes which may have hydrated the subducting oceanic lithosphere (Pararas-Carayannis, 1994; Seno & Yamanaka, 1996). Usually, shallow normal faulting occurs in the trench-outer rise region, as well as on the overriding Eurasian plate and the outer slope of the Japan Trench (Seno & Gonzalez, 1987).

Seismicity of Honshu - Along the northern segment of the Honshu arc, there is a triple seismic zone with variable degrees of seismicity due to regional stress fields (Kewakatsu & Seno, 1983; Seno & Takano, 1996; Seno, 1999b) (Fig. 6). It has been proposed that northern Honshu may be a separate microplate (Seno, 1999a). It has also been postulated that the subduction zone off Miyage Prefecture – where the 2011 tsunami was anomalously high – has a double zone of seismicity (Seno & Pongsawat, 1981; Seno & Kroeger, 1983).

Small earthquakes occur frequently along the east side of Honshu. Stronger earthquakes of M6.0 and large earthquake M7.0 occur less frequently and intermittently. Such earthquakes usually result from normal-types of faulting in areas where the shear stress is predominant - thus less likely to

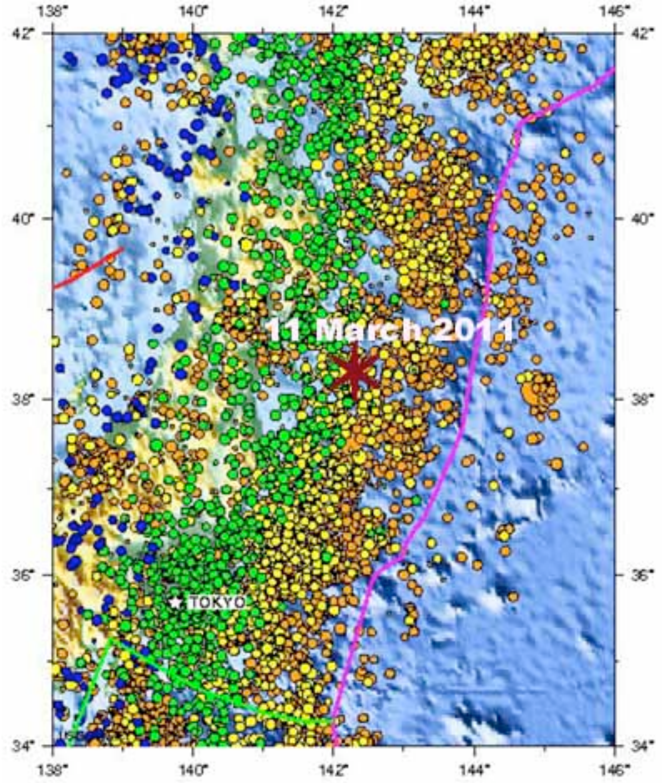

Fig. 5. Seismicity of Japan. Epicenter of the 11 March 2011 earthquake.

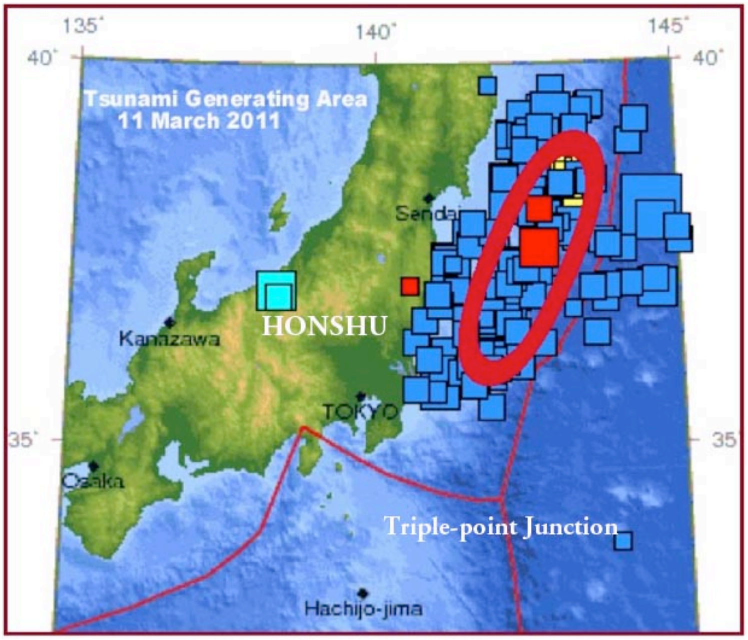

Fig. 6. Aftershocks and Tsunami Generating Area (Modified USGS mapping of major aftershocks).

generate great tsunamis. Earthquakes of M8.0 or greater occur infrequently on the average every 50 to 100 years. Such mega-thrust earthquakes involve mainly a mechanism where the compressional stress is predominant and their large vertical displacements are the cause of destructive tsunamis. The great Meiji Sanriku earthquake of 1896 off the Tōhoku region was such an event. It generated a destructive tsunami with waves reaching as high as 38 meters along the Sanriku coast. Another earthquake known as the 1933 (Shōwa) Sanriku Earthquake, generated another destructive tsunami. The March 11, 2011 earthquake (Mw9.0) had many similarities with the 1896 event (Pararas-Carayannis, 2009; 2011). All such tsunamigenic events in the past were shallow (about 20 km focal depth) and involved a thrust mechanism of compressional stress, which resulted in the uplift of the overriding tectonic plate, as well as in great horizontal movements that disturbed the sedimentary layers on the accretionary prism.

4. PAST AND RECENT DESTRUCTIVE TSUNAMIS

The Sanriku coast in particular and other and areas in the Tōhoku region have been impacted by numerous large tsunamigenic earthquakes. The historic record shows that a total of 65 destructive tsunamis struck Japan between A.D. 684 and 1960 (Pararas-Carayannis, 1982; 2000). As early as 18 July 869 (also reported as July 13, 869), an earthquake with an estimated magnitude of 8.3 generated a tsunami along the Sanriku coast, which resulted in the loss of 1,000 lives and the destruction of hundreds of villages. On 3 August 1361, another tsunami destroyed 1,700 houses in this same area and killed a large number of people. On 20 September 1498, 1,000 houses were washed away and 500 deaths resulted from a tsunami, which struck the Kii peninsula. Kyushu was struck by a destructive tsunami in September 1596. Great loss of life occurred on 31 January 1596 from a tsunami on the island of Shikoku, affecting also a number of regions in Honshu.

On 2 December 1611 another destructive tsunami struck Keichō killing almost 3,000 people along the Sanriku coast. The same tsunami killed more than 3,000 people in the Nanbu-Tsugaru area. Another earthquake on 17 February 1793 generated a tsunami that struck the Sanriku coast killing a number of people. On August 23, 1856, a strong offshore earthquake off the Sanriku coast generated another destructive tsunami.

The great Meiji Sanriku earthquake of 15 June 1896 generated a tsunami, which resulted in 27,122 deaths, thousands of injuries and the loss of over 10,000 structures and of more than 7,000 boats and ships. On 3 March 1933 the Shōwa Sanriku Earthquake generated a tsunami that stuck the Sanriku area. The maximum wave height at Ryōri Bay was 28.7 meters. The waves killed more than 3,000 people, injured hundreds more and destroyed approximately 9,000 homes and 8,000 boats. In December 1944, another offshore earthquake near central Honshu generated a tsunami that caused almost 1,000 deaths and the destruction of over 3,000 houses. The Nankaido tsunami, on 21 December 1946, resulted in 1,500 deaths and the destruction of 1,151 houses (Pararas-Carayannis, 1982). The 11 March 2011 earthquake generated the most destructive tsunami in recent times in the same general area. Given the history of catastrophic tsunamis along the Sanriku region, this latest event was expected to occur – although its timing could not be forecasted.

5. TSUNAMI SOURCE MECHANISM

The March 11, 2011 quake had characteristics of severity of tsunami generation usually associated with slow rupture velocity within compacted, sedimentary layers. Because of their tsunamigenic efficiency, such events are known as tsunami earthquakes. The 2011 earthquake had a complex focal mechanism, which involved mainly reverse thrusting and compression, but also multiple parallel ruptures, as well as extensive lateral and vertical sediment displacements - which contributed to the tsunami's severity.

The present evaluation includes a review of the combined rupturing impact on both the subducting Pacific oceanic lithosphere and on the overriding Eurasian tectonic plate, as well as on the large vertical tectonic crustal displacements. Additionally examined are the spatial and time sequence of foreshock and aftershock distribution, the clustering of aftershocks, the three-dimensional dynamics of shallow and deeper subduction processes, the effects of temporal elastic deformation caused by faulting and the collateral impact on the sediments of the accretionary prism. Finally, a comparison is undertaken of source characteristics of the destructive tsunamis of 1896 and 1933 in the same general area off Sanriku's coastlines. Although the 2011 earthquake occurred slightly to the south of the 1896 event, it had many similar source characteristics. The similarities and differences are discussed in a subsequent section.

5.1 Examination of Foreshocks and Aftershocks

5.1.1 Foreshocks

The main earthquake was preceded on 9 March 2011 by a large Mw7.2, shallow (less than 30 km), foreshock, followed by three more with magnitude greater than 6. The large foreshock occurred at 38.42N, 42.83E a little north of the subsequent great earthquake of March 11. Subsequent aftershocks prior to the main earthquake, spread to the north, but several of the larger events appeared to have migrated towards the eventual nucleation region of the 11 March 2011 main earthquake, at 38.30N, 142.34E (USGS). None of the foreshocks generated a tsunami.

5.1.2 Aftershocks

Examination of aftershock distribution indicates that the seismic energy of the March 11, 2011 earthquake was mainly released about 100 km off the coast of Miyagi and Fukushima Prefectures. About fifty minutes following the main quake on March 11, there were a large number of aftershocks, the largest having a magnitude of 7.1 (Table 1). Shortly afterwards, 35 more aftershocks larger than magnitude 5.0 and 14 larger than magnitude 6 were recorded (UGSS). By mid-March 2011 more than 250 aftershocks with magnitudes of over 5.0 had occurred and 25 of these had magnitudes over 6.0. Strong, shallow aftershocks with magnitudes greater than 6 were recorded on March 27 and 28.

Table 1. Main Earthquake and Major Aftershocks in the First 71 minutes (Mw8.9 assigned to main earthquake – revised later to Mw9 and Mw9.1)

UTC DATE-TIME 2011/03/11	Mag	Lat deg	Long deg	Depth km
05:46:24	9	38.322	142.369	24.4
06:06:11	6.4	39.025	142.316	25.1
06:07:22	6.4	36.401	141.862	35.4
06:15:46	6.8	36.126	140.234	30.2
06:25:51	7.1	38.106	144.553	19.7
06:48:47	6.3	37.993	142.764	22.3
06:57:15	6.3	35.758	140.992	30.2

5.1.3 Clustering of Aftershocks

Cluster algorithm analysis of aftershocks in chronological sequence (Peter Zhol - personal communication), determined a big cluster of 260 events; a second cluster of 120 events and a third cluster of 60 events, as well as 20 very small clusters - typically one or two events each (Fig. 7).

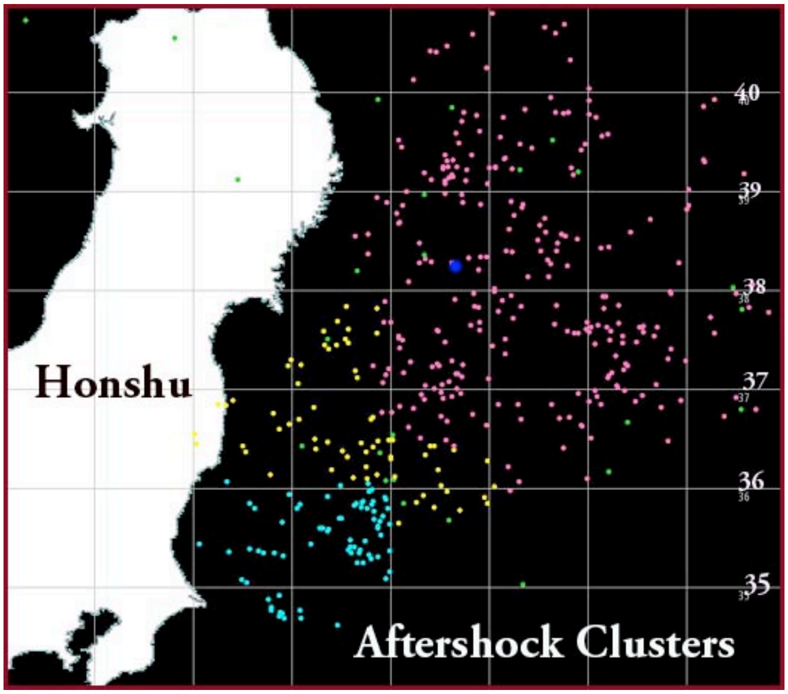

Fig. 7. Three Major Clusters of Aftershocks (*Depths (modified after Peter Zhol - personal communication*)

Many of the aftershocks may have occurred on unmapped, minor faults both in the intra-plate region as well as on the outer rise of the subducting plate. Plotting the aftershock focal depths along eastern Honshu indicated that there was a spectacular peak at a focal depth of about 24-25 km (Fig 8). The significance of this to tsunami generation was evaluated in terms of regional, spatial subduction geometry, slip, crustal movements and sediment displacements. Buckling of the crust due to subduction friction probably activated many minor, normal faults, which gave rise to subsequent aftershocks - even outside the tsunami generating region on the outer ridge of the subducting plate. Indeed the aftershock distribution was extensive, covering an area that was approximately 500 km long and 300 km wide.

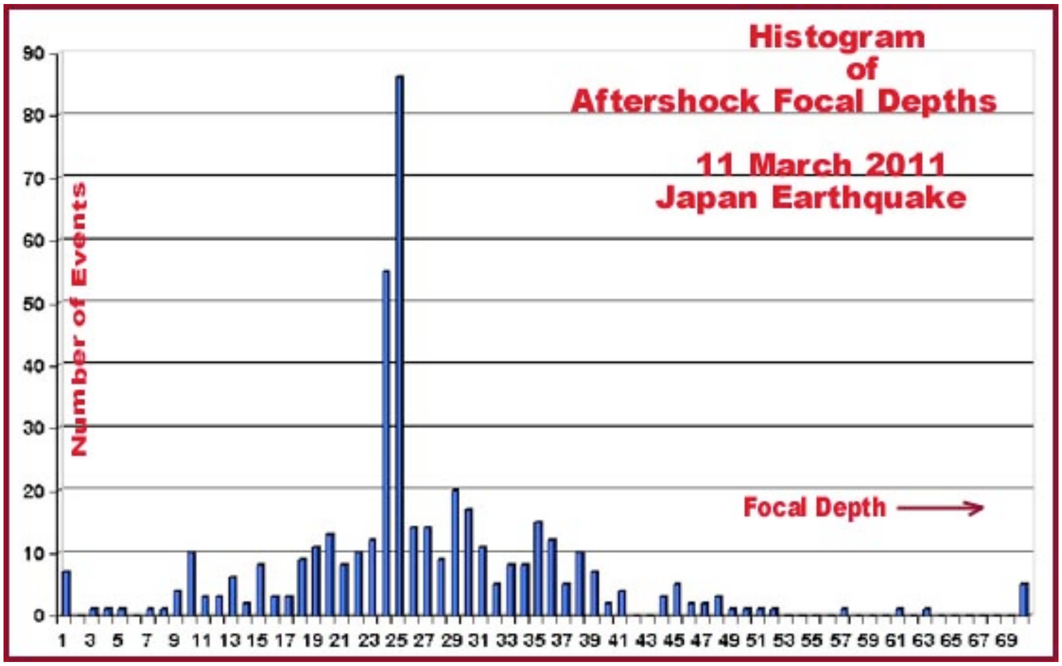

Fig. 8. Histogram of Aftershock Focal Depths (modified after Peter Zhol - personal communication)

5.1.4 Examination of Rupture Propagation and Duration

The effects of sediments on earthquake rupture velocity and tsunami generation for other subduction regions such as Makran in the North Arabian Sea, the Sunda Trench segment in the Andaman Sea and the Mid-America Trench have been examined (Pararas-Carayannis, 1992; 2005; 2006). In all these regions of subduction block motions of consolidated sediments were associated with bookshelf faulting, which contributed to slow-rupturing, silent and deadly tsunami-earthquakes. The block motions were extremely shallow and occurred within subducted sediments where there was a lot of shear - thus the rupture was slower in speed. In all of these cases, the degree of sediment consolidation along the plate boundary appeared to have been a key factor in locking slippage on the megathrust region of the tectonic boundary, then releasing greater energy when the stress thresholds were exceeded.

Apparently, the region where the 11 March 2011 Tohoku earthquake occurred had reached a very high level of stress. However, since subduction near Honshu does not follow a straight fault line along the tectonic boundary as defined by the Japan Trench, most large tsunamigenic earthquakes along the Sanriku region - even the most destructive - involve relatively short ruptures, but proportionately large slips. Although their seismic energy release may be quite high, the affected crustal blocks tend to be smaller because of existing asperities.

The 2011 earthquake – like most large earthquakes – had a complex rupture which exhibited a variation in velocity. The rupture propagation, duration, and displacements were investigated by numerous researchers using different models and techniques (Wang and Mori, 2011; Shao et al., 2011; Ammon et al., 2011). Accordingly, the earthquake ruptured the interplate boundary off-shore east Honshu, with fault displacements of up to 40 m, variable rates of propagation and a rupture duration which was estimated to range from 150 to 170 seconds. The estimates were relatively consistent. For example, data recorded by the dense USArray network in Japan, indicated that the quake exhibited a variable rupture propagation, which ranged from about 1.0 to 3.0 km/s for the high-frequency radiation and lasted approximately 170 seconds. Significant changes of physical properties along the fault plane may be the reason for the variability in the velocity of rupture propagation. The overall rupture length was estimated to be about 450 km long (Wang and Mori, 2011).

5.1.5 Examination of Seismic Energy Release

Inversion of teleseismic P waves and broadband Rayleigh wave observations with high-rate GPS recordings indicated a moment of 3.9 — 10^{22} Nm (Mw 9.0) and a centroid time of 71 s. (Ammon et al., 2011). Teleseismic body and surface wave analysis of both broadband body waves and long period seismic waves (Shao et al, 2011) determined the total seismic moment to be 5.8 — 1022 Nm. Furthermore, the resulting rupture models showed a steady increase of moment rate for the first 80 seconds and an initial rupture speed of 1.5 km/s mainly in a northwesterly direction. Subsequent rupturing in a southwestward direction continued at a speed estimated at about 2.5 to 3.0 km/s. As stated, changes in physical properties of crustal and sedimentary material may be responsible for the variation in speed. Usually, areas of low rupture velocity are associated with large energy release along the fault plane, while high rupture speed may be associated with lower energy release.

5.1.6 Examination of Crustal Movements

The 2011 earthquake was a megathrust event with the Pacific plate moving underneath the Eurasian plate. As a result, the landmass of Honshu Island moved in an east-southeasterly direction. Based on the Global Positioning System, the Geospatial Information Authority in Tsukuba, Japan, estimated that the Oshika Peninsula near the epicentral area moved by a little over 5 meters (17 feet) eastward and subsided by a little over 1 meter (4 feet). Additionally, the Geospatial Information Authority stated that there were land mass movements in many areas of Honshu, from the northeastern region of Tohoku to the Kanto region, including Tokyo. Slip and fault displacements were estimated to be up to 40 meters (Ammon et al., 2011). However, direct measurement of seafloor deformation near the trench axis by JAMSTEC (Japan Agency for Marine Earth Science and Technology) indicated the average seafloor displacement of 50 m within the 40 km west of the trench axis. Such large slips near trench are not uncommon for great subduction earthquakes of Mw>8. Finally, based on the kinematic rupture history, it is estimated that a vertical uplift of up to 10 meters on the east side of the fault and nearer to the Japan Trench axis and asperity, was the cause of the destructive tsunami.

The existence of thrust earthquakes in this segment off Honshu indicates that either the sediments along the plate boundary become sufficiently well consolidated and dewatered at about 70 km from the deformation front, or that older, lithified rocks are present within the forearc so that stick-slip sliding behavior becomes possible when the stress exceeds a critical level. Fig. 9 , illustrates that the maximum slip occurred along a relatively shallow region ranging 140-180 km in length, in both directions above the quake's hypocenter. At the present time there is not sufficient data or surveys of the area to fully evaluate the effect of sediments on the subduction dynamics off the northeast coast of Honshu.

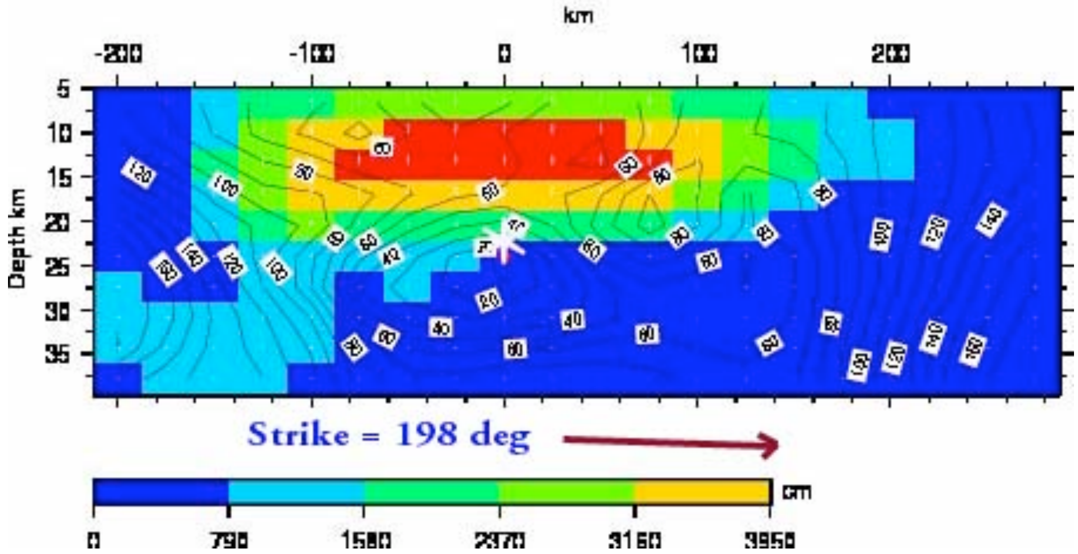

Fig. 9. Cross-section of the quake's slip distribution. The strike direction of the fault plane is indicated by the red arrow and the hypocenter location and depth of the March 11, 2011 earthquake are denoted by the white star. Contours show the rupture initiation time in sec. (modified after Shao et. al. 2011).

5.1.7 Tsunami Source Area

The 2011 Sanriku earthquake packed a great deal of energy. However, its tsunami generating source area was relatively small compared to those of the great Sumatra (2004) and Chile (2010) earthquakes (Pararas-Carayannis, 2005, 2010). The Sumatra earthquake had a rupture that propagated also at varying speeds along two segments of the Sunda tectonic boundary and its overall tsunami source area was almost 1,300 km long, about 300 km wide and involved large slip.

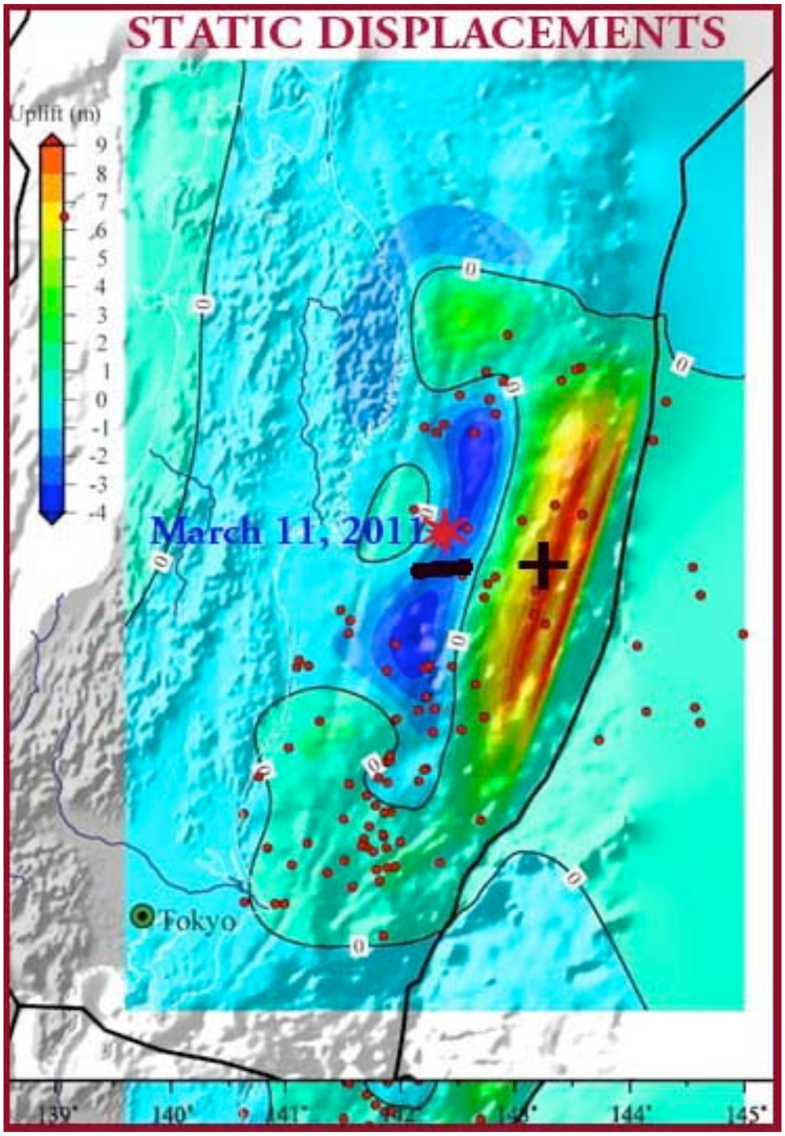

Fig. 10. Predicted Vertical Static Displacements (positive and negative) based on the inverted slip model (Cross-section of slip distribution shown in Fig indicating maximum tectonic uplift of almost 10 meters (modified after Shao et al. 2011).

By comparison, the 2011 Sanriku earthquake had an extensive aftershock region that was almost 450-km long and 200-km wide, but the source region that generated the large tsunami was rather compact. Focal mechanism analysis indicates dipole crustal movements involving both subsidence and uplift. Apparently, most of the positive vertical static displacements occurred closer to the Japan Trench on the accretionary prism (Fig. 10). Also, teleseismic P waves and broadband Rayleigh wave observations (Ammon et al., 2011) support the conclusion that most of the significant displacements that generated the larger tsunami occurred in the first 80 seconds after rupture initiation.

What contributed to the higher tsunami heights were the earthquake's up-dip rupture expansion, mainly above the quake's hypocenter (at 20-24 km depth), which resulted in extensive additional vertical and horizontal movements and uplift of sediments on the overriding plate - which extended almost to the edge of the Japan Trench. Although the overall tsunami source area was about 300 to 350-km long and about 150 to 175-km wide, the spatial and temporal sequencing and clustering of major aftershocks and the energy release indicate that the main source area that generated the higher tsunami was about 120-140 km long and about 80 km wide (Fig. 11).

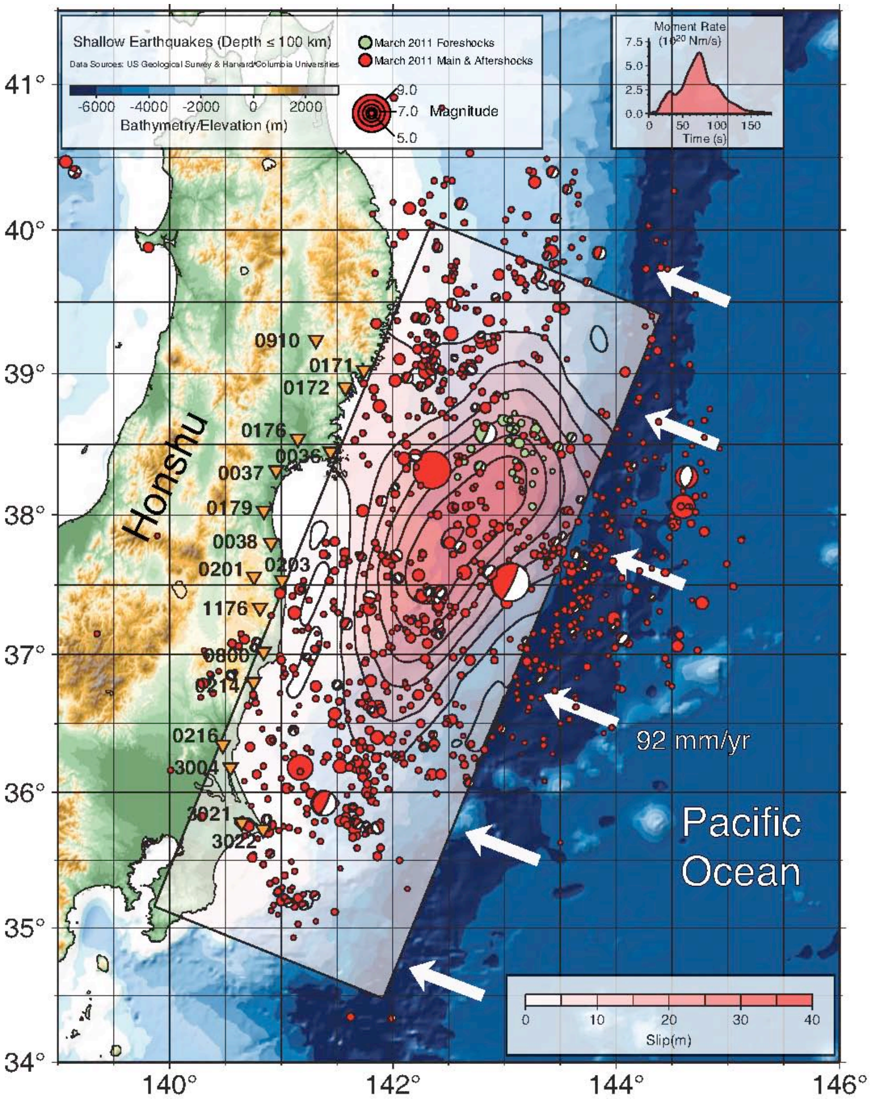

Fig. 11. Tsunami Generating Area showing the epicenter of the main earthquake on March 11, 2011, a major aftershock with magnitude 7.1 fifty minutes later and 172 aftershocks which were recorded by the USGS by March 12, 02:04:53 UTC 2011(After Ammon et al., 2011)

6.1.8 Tsunami Source Mechanism

Subduction of the Pacific tectonic plate beneath the Eurasian plate resulted in the great Sanriku earthquake of 2011. The earthquake involved primarily reverse thrust compression, as well as strike slip shear and east-southeast trending lateral movement of the overriding Japan volcanic arc of the Eurasian plate. The following source mechanism scenario is proposed to explain the larger height tsunami that struck northeastern coastal areas of Honshu and particularly the coasts of Miyagi and Fukushima Prefectures (Fig. 12).

Initial rupturing begun at the earthquake hypocenter focal depth of 24.4 km and expanded upward on the accretionary prism towards the ocean floor, first through well-compacted non-hydrated sedimentary layers and subsequently through fully hydrated layers. Rupturing continued in this manner for the first 80 seconds - propagating at the rate of about 1.5 km/sec for an approximate distance of about 120 km in a northwesterly direction from the epicenter location. The initial combination of reverse thrust compression, strike slip shear and east-southeast lateral movement and compression of the sedimentary prism, resulted in slip and fault displacements estimated to be up to 40 meters, maximum eastward movement of land mass estimated to be as much as 5 meters at the surface (17 ft. maximum near Oshika Peninsula) and subsidence estimated to be about 1.2 m.

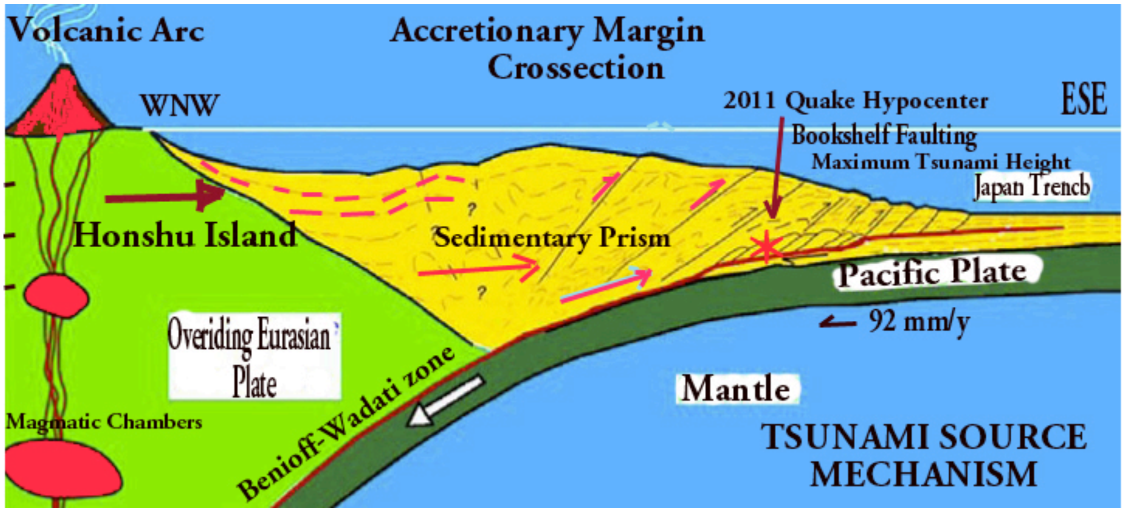

Fig. 12. Postulated Crossection of the Accretionary Margin east of Honshu Island. Compression of the Sedimentary Prism and Subsequent Normal and Bookshelf Faulting contributed to the Tsunami's Source Mechanism and to greater Tsunamigenic Efficiency.

At first, the sediments on the accretionary prism along both east and west of the hypocenter compressed elastically. However the elastic deformation was short-lived, as in the next few seconds the rupturing process nucleated existing normal faults on the continental shelf on both sides of the rupture, which also begun to fail in sequence. Additionally, the reverse thrust motions and lateral compression ruptured the sedimentary layers of the accretionary prism, which begun failing sequentially in a bookshelf fashion creating several parallel and en-echelon thrust faults along a much wider zone of deformation that extended westward toward the Japan Trench. Because of the lateral compression of the sedimentary layers and the subsequent failure due to bookshelf faulting, large volumes of sediments begun thrusting upward with fault dips becoming progressively steeper on the east side of the initial rupture and along the eastern zone of the accretionary prism closer to the Japan Trench. In this eastern region the greater volume of up-thrusted sediments contributed significantly to the generation of the higher tsunami that was generated in the first 80 seconds. Thus, the larger tsunami was generated along a zone of deformation that was about 120-140 km long and about 80 km wide off the coast of the Miyagi and Fukushima Prefectures – the regions that also experienced the greater tsunami devastation.

Subsequent rupturing in a southwestward direction continued for approximately 100 seconds at a speed estimated at about 3.0 km/s. for a total distance of about 300 kms. This region did not experience as much bookshelf faulting and there was lesser upward displacement of sediments and a smaller offshore tsunami. Thus the tsunami that struck coastal sites along the Ibaraki Prefecture was not as high. Studies of the rupture process in space and time (Honda et al., 2011) also confirm this conclusion.

7. EVALUATION OF TSUNAMIGENIC EFFICIENCY

As stated, W-phase inversion indicated a moment of 3.9 x 10^{22} Nm (Mw 9.0) and a centroid time of 71 s. (Ammon et al, 2011). The back-projection method - which used data recorded on the USArray network (Wang and Mori, 2011) - estimated a rupture propagation with variable speed ranging from about 1.0 to 3.0 km/s for about 450 km in length in approximately 170 seconds.

The variable rupture propagation and change in directionality indicate that the tsunami generation area can be divided into two distinct segments along a wide zone of deformation. Apparently, the most significant disturbance of sediments occurred in the first segment when the rupture speed was slower and thus the tsunami height was greater. Since the two initial pulses occurred at 30 and 80 seconds in a rupture segment located 50 to 70 km northwest of the epicenter, we can conclude that the higher tsunami was generated along this segment during that time interval following the main earthquake. The third impulse which occurred about 250 km southwest of the epicenter about 180 seconds after the main shock, is indicative of higher rupture velocity in a southwestward direction from the quake's hypocenter and of second region of tsunami generation of much lesser height with lesser sediment contribution. The observed three-pulse energy release is also supported by the cluster algorithm analysis of the aftershocks, which indicates the segmentation of the tsunami generating area. As previously stated, there was a big cluster of 260 events, followed by a second cluster of 120 events and by third cluster of 60 events - as well as 20 very small clusters, most outside the tsunami generation area – some on the outer rise of the subducting tectonic plate (Fig. 7). These variations indeed reflect differences in the strength of physical properties on both the subducting and overriding tectonic plates – such as rigidity, compaction and degree of hydration/serpentinization - along the 450 km fault(s) that ruptured sequentially when the 2011 Tohoku earthquake struck.

Based on the above-described evaluation, we conclude that the great height of the 2011 tsunami along the Honshu's coastlines was caused by the crustal displacements due to up-thrust faulting and by the displacement and excessive uplift of sediments along the accretionary prism of the overriding tectonic plate, as it thrusted east-southeast towards the Japan Trench by as much as 5 meters (about 17 ft) in certain areas and probably more at the décollement depth. To what extent and what volume of sediments were uplifted cannot be estimated since the displacements were non-uniform over the entire length of the two main segments of the rupture zone. However, we can conclude that most of the sediment displacements occurred mainly along the segment of the fault off the Miyagi and Fukushima Prefectures where the seismic energy release was greater (Fig. 11). As stated, there was lesser seismic energy release along the segment off the Ibaraki Prefecture.

The amount of additional sediment uplift of the 1896 Sanriku earthquake (Fig. 13) was examined in the past (Tanioka & Satake, 1996; Tanioka & Seno, 2001). This event was characterized as a tsunami earthquake because of its slow rupturing velocity and weak ground motions along the Sanriku coast.

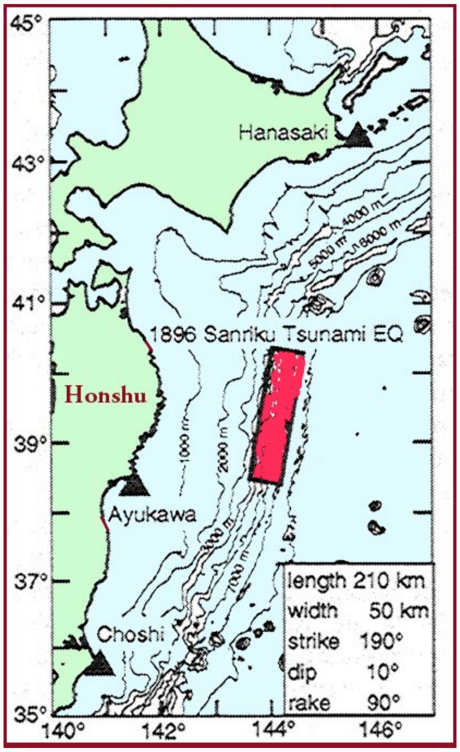

Fig. 13. Estimated earthquake fault parameters and generation area of the 1896 tsunami as determined by reverse wave refraction from three tide gauges in the region (modified original graphic by Tanioka & Satake, 1996; also shown in Tanioka & Seno, 2001 with a change of fault dip from 20 to 10 degrees). The sum of elastic deformation and the additional uplift of sediments were used with three different models of displacement to estimate total ocean floor deformation.

In trying to estimate the slip for this event by modeling, it was determined that a postulated 20° dipping fault along the top of the subducting plate, offered a match for both the observed seismic response and the tsunami, but required an estimated slip displacement of 10.4 meters. However, when a shallower fault dip of 10° was used and the additional uplift of sediments was taken into account, a slip ranging from 5.9 to 6.7 meters was obtained, which was in better agreement with the tsunami's waveforms recorded at three tide stations. By revising the fault modeling, Tanioka & Seno (2001) estimated the magnitude of the 1896 earthquake to be Mw=8.0-8.1. However, this was an underestimate as the magnitude of the 1896 earthquake was probably similar or even greater to that of 2011. Also, of the three displacement models they considered for the contribution of sediment uplift to tsunami generation, the one shown in Fig. 14 below - involving the only the leading edge of the accretionary prism - is more realistic but would still underestimate the actual sediment uplift of the 1896 tsunami. Apparently, the 2011 tsunami involved sediment uplift over a much wider area on the accretionary prism and thus it would be difficult to estimate quantitatively the effect on ocean surface displacement and wave heights at the source region.

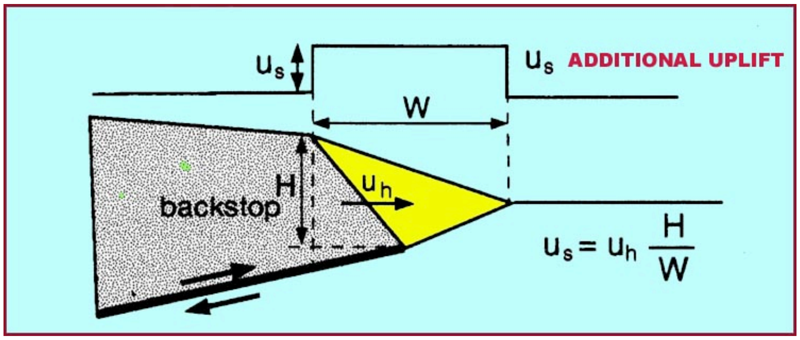

Fig. 14. Uplift of sediments by compressional forces. One of three models of displacements along the leading edge of the Accretionary Prism which was used to estimate additional contribution to tsunami height from a sediment uplift process for the 1896 event (modified after Tanioka & Seno, 2001).

8. EVALUATION AND COMPARISON OF THE 1896, 1933 AND 2011 SANRIKU EARTHQUAKES

The March 11, 2011 earthquake was one of the largest in the last century. Most recent great earthquakes struck Indonesia in 2004 and Chile in 2010. All of recent great earthquakes had rupture zones that extended for several hundred of kilometers and slips, which were 10 meters of more.

8.1.1 Destruction and Fatalities

Both the 1896 and the 2011 quakes generated extremely destructive tsunamis along the Sanriku coast. The 1933 tsunami was also very destructive (Iida et al., 1967; Hatori et al. 1982; Pararas-Carayannis, 2005). The estimated source region of the 1896 tsunami (Fig.) was somewhat north of that of 1833 and of 2011.

There were many similarities in the height of the tsunami waves and thus to the degree of destructiveness and the number of fatalities for all three events. For example, thirty to sixty minutes following the 1896 earthquake, tsunami waves begun to strike the Sanriku coastal region as well as the southern coasts of Hokkaido. The death toll of the tsunami was 26,360. At the village of Tarō only 36 people of its total population of 2,000 survived while all infrastructure and most of the houses were destroyed (Nakao, 2009). The 1933 tsunami was equally devastating. A total of 3,064 people were killed and 1,092 were injured. At Yoshihama, close to Ryori Bay, the 1933 tsunami was responsible for 982 deaths. The death toll of the 2011 tsunami was given as 13,843 at the end of April, with another 14,030 people missing. The impact of the Fukushima nuclear disaster may have a long-term collateral impact and will add to the total death toll.

8.1.2 Seismic Intensities

The great earthquakes of 1611 (Keichō), of 1896 (Meiji Sanriku) and of the 2011 (Sanriku) were not associated with strong ground motions over large areas but generated extremely devastating tsunamis. All three involved reverse faulting with slow rupturing within thick sedimentary layers. By contrast the 1933 "Showa" quake occurred on a normal fault.

The ground motions of the 1896 earthquake were not substantial and seismic intensities ranging from 2 to 4 were assigned to this event (JMA scale) for a relatively small area of Sanriku (Fig. 15). The quake's rupture velocity was relatively slow, indicating the presence of compacted sedimentary layers in the source region. However, the generated tsunami was extremely high, as this was a distinct tsunami earthquake with a slower fault slip than that which usually occurs during normal earthquakes. The ground motions of the 1933 earthquake were much stronger and were assigned an intensity of 5. However, the tsunami it generated was not as high as that of 1896. Although the 2011 event was also characterized as a tsunami earthquake, strong ground motions were felt as far away as Tokyo. The stronger ground motions were probably generated along the second segment of the earthquake’s rupture, which was associated with higher propagation velocity of up to 3km/sec.

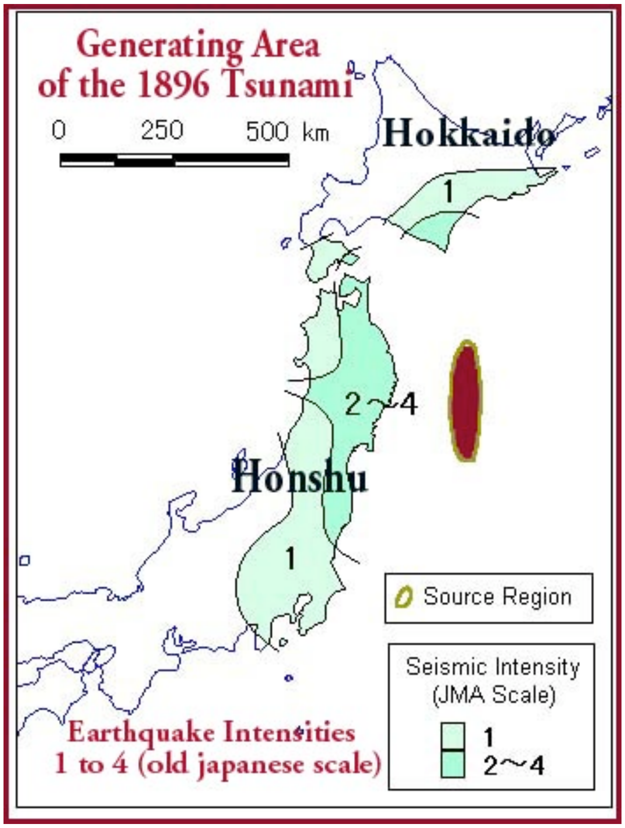

Fig. 15. Seismic Intensities of the 1896 Earthquake. Approximate generating area of the tsunami (modified after Japan Meteorological Observatory, 1896)

8.1.3 Source Mechanisms

Both the 2011 Sanriku earthquake and the 1896 "Meiji" earthquake occurred on reverse faults and had characteristics of severity of tsunami generation usually associated with slower initial fault slips and slow rupture velocities within compacted sedimentary layers. Both had slow rupture velocities initially - mainly within compacted sedimentary layers - thus resulting in greater vertical and horizontal displacements of sediments along the accretionary prism near the Japan Trench. Both events can be characterized as "tsunami earthquakes". By contrast the 1933 "Showa" quake occurred on a normal fault. Although this was also a great earthquake and generated a very destructive tsunami, its impact was not as severe as the 1896 and the 2011 events.

8.1.4 Tsunami Runup Heights

As stated, the March 11, 2011 tsunami impact on Honshu's coasts was similar to those of 1896 and 1933. All three tsunamis reached the shores of Honshu within 30 to 40 minutes after the main shocks were felt. The maximum heights for all three tsunamis occurred at Ryōri Bay in Sanriku, Iwate

Prefecture. The height of the 1896 tsunami was 38.2 meters, the highest ever in Japan since the tsunami of 1868 (Fig. 16). The maximum height of the 2011 tsunami was roughly the same as that of 1896, approximately 38 meters at the village of Ryōri. The 1933 tsunami in the same area reached a height of 23.0 m.

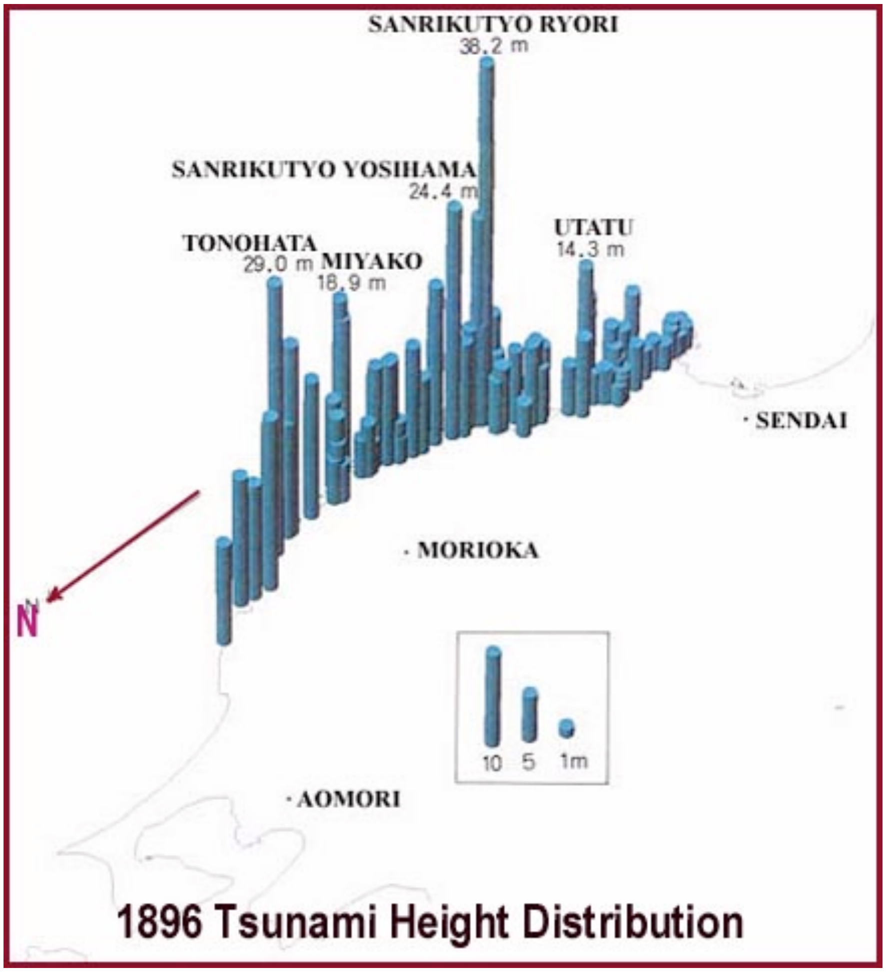

Fig. 16. The *1896 Maximum Tsunami Height Distribution North of Sendai (modified after Hatori et al., 1982?)*

The far field impact of the 1896 tsunami was greater than that of 2011. In 1896, waves up to 9 meters (30 feet) struck the Hawaiian Islands, causing extensive destruction to wharves, boats and houses (Pararas-Carayannis, 1969). The waves of the 2011 tsunami were destructive but ranged from 2 to 3 meters (7 to 11 feet). Similarly in California a wave of about 3 meters (9.5 feet) was observed in San Francisco in 1896, but the 2011 was less and in Crescent City the maximum runup height of the 2011 tsunami was about 2.5 meters.

9. SUMMARY AND CONCLUSIONS

The anomalously high 2011 tsunami which occurred along Honshu's east coast resulted from a combination of crustal deformations of the ocean floor due to the upthrust tectonic motions of the earthquake, augmented by additional uplift due to large coseismic lateral movement which compressed and deformed sediments along the accretionary prism on the overriding tectonic plane near the Japan Trench. The event was a "tsunami earthquake" in the sense that it was mostly associated with a slow rupturing process and lateral movement within shallow and highly compacted sedimentary layers.

The deformation occurred randomly along parallel and en-echelon faults, which failed in a sequential bookshelf manner. Most of the energy release and deformations that generated the huge tsunami occurred along the shallow eastern segment of the fault off the Miyagi Prefecture, while the segment off the Ibaraki Prefecture – where the rupture process was rapid – released minor seismic energy and resulted in lesser compaction and deformations of the sedimentary layers. Because of the complexity of the rupturing process, the extent of additional uplift due to buckling of the sediments in the tsunami generation area off the Miyagi segment of the fault is difficult to estimate. However, both the 1992 Nicaragua and 2004 Sumatra earthquakes demonstrated that bookshelf failure of sedimentary layers could generate anomalously high tsunamis. Apparently, the same mechanism was responsible for the high tsunami generated in the offshore area off Honshu when the March 11, 2011 earthquake struck.

The great 1896 Sanriku earthquake was also a tsunami earthquake with a similar mechanism of tsunami generation enhanced by sediment deformation and uplift. Finally, the March 2011 event may have released most of the stress that had accumulated – thus ending a seismic cycle for this particular region off the Sanriku coast. However, due to energy transference, a new seismic cycle of stress has begun for the adjacent regions, which will culminate in another large tsunamigenic earthquake in the near future – perhaps in the next two to four years. A large tsunamigenic earthquake with moment magnitude up to Mw 8 can be expected to occur either to the north closer to Hokkaido and the Kurile Islands, or to the south closer to the Izu-Ogasawara Trench area.

REFERENCES

Ammon C. J., Thorne L., Kanamori H., Cleveland M., 2011. “A rupture model of the great 2011 Tohoku earthquake”. Accepted May 18, 2011; Online published.

Hatori T., Aida I, Koyama M and T. Hibiya, 1982. Field Survey of the Tsunamis In Inundating Ofunato City - The 1960 Chile and 1933 Sanriku Tsunamis. Bull. of the Earthquake Research Institute, Vol. 57, pp. 133-150.

Honda R., Yukutake Y., Ito H., Harada M., Aketagawa T., Yoshida A., Sakai S. , Nakagawa S., Hirata N., Obara K. and Kimura H., 2011. “A complex rupture image of the 2011 Tohoku earthquake revealed by the MeSO-net”. TERRAPUB Report (Received April 10, 2011; Revised May 18, 2011; Accepted May 29, 2011 and published Online).

Iida, K., D.C. Cox, and Pararas--Carayannis, G., 1967. Preliminary Catalog of Tsunamis Occurring in the Pacific Ocean. Data Report No. 5. Honolulu: Hawaii Inst. Geophys. Aug. 1967.

Kawakatsu, H., and T. Seno, 1983. Triple seismic zone and the regional variation of seismicity along the northern Honshu arc. J. Geophys. Res. 88 4215-4230, 1983.

Nakao, M., 2009. "The Great Meiji Sanriku Tsunami June 15, 1896 at the Sanriku coast of the Tohoku region". Retrieved 2009-10-18.

Pararas-Carayannis, G. 1992. The Earthquake and Tsunami of 2 September 1992 in Nicaragua http://drgeorgepc.com/Tsunami1992Nicaragua.html

Pararas-Carayannis, G. 1982. The historic record shows that a total of 65 destructive tsunamis struck Japan between A.D. 684 and 1960

Parras-Carayannis G. 1983, The Earthquake and Tsunami of 26 May 1983 in the Sea of Japan

Pararas-Carayannis, G., 1994. The Earthquake and Tsunami of July 12, 1993 in the Sea of Japan/East Sea - The Hokkaido "Nansei-Oki" Earthquake and Tsunami http://www.drgeorgepc.com/Tsunami1993JAPANOkushiri.html

Pararas-Carayannis, G., 2000. Major Earthquakes in Japan in the 20th Century http://drgeorgepc.com/EarthquakesJapan.html

Pararas-Carayannis, G., 2005. Earthquake and Tsunami of December 26, 2004, in Indonesia http://drgeorgepc.com/Tsunami2004Indonesia.html

Pararas-Carayannis G., 2006. Potential of Tsunami Generation along the Makran Subduction Zone in the Northern Arabian Sea, Case Study: The Earthquake and Tsunami of November 28, 1945, Science of Tsunami Hazards, Vol. 24, No. 5 pp 358-384

Pararas-Carayannis, G. 2006b. The Earthquake and Tsunami of 28 November 1945 in Southern Pakistan http://drgeorgepc.com/Tsunami1945Pakistan.html

Pararas-Carayannis G., 2009. Earthquake and Tsunami of 3 March 1933 in Sanriku, Japan. http://drgeorgepc.com/Tsunami1933JapanSanriku.html

Pararas-Carayannis G., 2010. Earthquake and Tsunami of 27 February 2010 in Chile - Evaluation of Source Mechanism and of Near and Far-field Tsunami Effects. Science of Tsunami Hazards, Vol. 29, No. 2. 2010. Also a summary at http://www.drgeorgepc.com/Tsunami2010Chile.html

Pararas-Carayannis, G., 2011a. The Great Tsunami of March 11, 2011 in Japan - Analysis of Source Mechanism and Tsunamigenic Efficiency. OCEANS 11, MTS/IEEE Proceedings, 2011

Pararas-Carayannis, G., 2011b. Earthquake and Tsunami of 11 March 2011 in Sanriku, Japan http://www.drgeorgepc.com/Tsunami2011JapanSanriku.html

Seno, T. and D. G. Gonzalez, 1987. Faulting caused by earthquakes beneath the outer slope of the Japan Trench. J. Phys. Earth 35 381-407, 1987.

Seno, T. 1999a. Is northern Honshu a microplate? Tectonophysics 115 177-196 1985

Seno, T. 1999b. Syntheses of the regional stress fields of the Japanese islands The Island Arc 8 66-79 1999.

Seno, T., and Y. Yamanaka, 1996. Double seismic zones, compressional deep trench - outer rise events and superplumes in Subduction Top to Bottom, edited by G. E. Bebout, D. W. Scholl, S. H. Kirby, and J. P. Platt Geophys. Monogr. 96 347-355 1996

Seno, T., and Y. Yamanaka, 1998. Arc stresses determined by slabs: Implications for mechanisms of back-arc spreading. Geopys. Res. Lett. 25 3227-3230, 1998

Seno, T., T. Sakurai, and S. Stein, 1981. Can the Okhotsk plate be discriminated from the North American plate? J. Geophys. Res. 101 11305-11315, 1996

Seno, T., and B. Pongsawat, 1981. A triple-planed structure of seismicity and earthquake mechanisms at the subduction zone off Miyagi Prefecture, northern Honshu, Japan Earth Planet. Sci. Lett. 55 25-36, 1981

Seno, T., and G. C. Kroeger. 1983. A reexamination of earthquakes previously thought to have occurred within the slab between the trench axis and double seismic zone, northern Honshu J. Phys. Earth 31 195-216, 1983.

Seno, T., and T. Takano, 1996. Seismotectonics at the trench-trench-trench triple junction off central Honshu Pure Appl. Geophys. 129 27-40, 1989.

Seno, T., and Y. Yamanaka, 1996. Double seismic zones, compressional deep trench - outer rise events and superplumes in Subduction Top to Bottom, edited by G. E. Bebout, D. W. Scholl, S. H. Kirby, and J. P. Platt Geophys. Monogr. 96 347-355, 1996.

Shao, G., Li X., Ji C. and T. Maeda, 2011. Focal mechanism and slip history of 2011 Mw 9.1 off the Pacific coast of Tohoku earthquake, constrained with teleseismic body and surface waves, Earth Planets Space, submitted, 2011.

Tanioka, Y., and K. Satake (1996). Fault parameters of the 1896 Sanriku tsunami earthquake estimated from tsunami numerical modeling, Geophys. Res. Letters, 23-13,1549-1552.

Tanioka, Y.; Seno T. (2001). "Sediment effect on tsunami generation of the 1896 Sanriku tsunami earthquake". Geophysical Research Letters 28 (17): 3389–3392.

Wang D. and Mori J. 2011. “Rupture Process of the 2011 off the Pacific Coast of Tohoku Earthquake (Mw 9.0) as Imaged with Back-Projection of Teleseismic P-waves”. *Earth Planets Space*, **, 1–5, 2011

Wei D. and Seno T. 1998. Determination of the Amurian Plate Motion. In Mantle Dynamics and Plate Interactions in East Asia, edited by Martin Flower, GeoDynamics Series., AGU, 1998

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