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FIELD SURVEY REPORT OF TSUNAMI EFFECTS CAUSED BY THE AUGUST 2012 OFFSHORE EL SALAVADOR EARTHQUAKE

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ABSTRACT

This report describes the field survey of the western zone of El Salvador conducted by an international group of scientists and engineers following the earthquake and tsunami of 27 August 2012 (04:37 UTC, 26 August 10:37 pm local time). The earthquake generated a tsunami with a maximum height of ~ 6 m causing inundation of up to 300 m inland along a 40 km section of coastline in eastern El Salvador.

** (Note: Presentation from the 6th International Tsunami Symposium of Tsunami Society International in Costa Rica in Sept. 2014 - based on the Field Survey Report of the tsunami effects caused by the August 2012 Earthquake which were compiled in a report by Jose C. Borrero of the University of California Tsunami Research Center. Contributors to that report and field survey participants included Hermann M. Fritz of the Georgia Institute of Technology, Francisco Gavidia-Medina, Jeniffer Larreynaga-Murcia, Rodolfo Torres-Cornejo, Manuel Diaz-Flores and Fabio Alvarad: of the Ministerio de Medio Ambiente y Recursos Naturales de El Salvador (MARN), Norwin Acosta: of the Instituto Nicaragüense de Estudios Territoriales(INOTER), Julie Leonard of the Office of Foreign Disaster Assistance (USAID, OFDA), Nic Arcos of the International Tsunami Information Center (ITIC) and Diego Arcas of the Pacific Marine Environmental Laboratory (NOAA – PMEL The figures of this paper are from the report compiled by Jose C. Borrero and are numbered out of sequence out of sequence from the compiled joint report. The quality of figures 2.2, 2.3 and 2.4 is rather poor and the reader is referred to the original report, as shown in the references).*

1. INTRODUCTION

El Salvador is located on the Pacific Coast of Central America bordered by Guatemala to the north and Honduras to the East (Figure 1.1). The Gulf of Fonseca at the eastern end of the country is a water body also shared by Honduras and Nicaragua. At just over 21,000 km2 and with 6 million inhabitants, El Salvador is the smallest and most densely populated country in Central America.

Figure 1.1 A political map of El Salvador. The Capital of San Salvador is indicated with a red star while red dots show the locations of the two tide stations that recorded the tsunami. Acajutla, the country's principal port in the west and La Union in the Gulf of Fonseca in the east. The area affected by the tsunami (Peninsula San Juan del Gozo) is near Acajulta.

The National Geophysical Data Center / World Data Service for Geophysics (NGDC/WDS) maintains a global historical tsunami event and run-up database. According to the database, 20 tsunamis were observed in El Salvador from 1859 to 2012, 15 of these are confirmed (validity 3-4) and 5 are questionable (validity 1-2). Nine of the sources were local, two were regional (Costa Rica, Guatemala) and nine were far field (Chile, Ecuador, Indonesia, Japan, Mexico, Russia, Alaska USA). A local tsunami in 1859 caused damage to warehouses and houses in La Union, El Salvador; a far field tsunami in Alaska 1957 caused damage to pilings in Acajutla, El Salvador. A local event on 26 February 1902 resulted in 185 deaths, 100 injuries and houses were washed out to sea at Barra de Santiago and Barra de la Pas, El Salvador. UNESCO's Intergovernmental Oceanographic Commission (IOC) and International Tsunami Information Center (ITIC) coordinated an international post-tsunami field surveys of the tsunami and its effects. It is doing so at the request of the Governments of El Salvador (GoES). The goals include:

· Promote sharing of data with affected countries
· Minimize logistical problems for visitors and hosts
· Link visitors to country collaborators
· Provide the governments with a summary of the ITST findings

The coordination for this effort will be handled by the International Tsunami Information Center, in close coordination with the IOC and the affected country.

The Pacific Tsunami Warning Center (PTWC) issued its first information bulletin on the El Salvador event eight minutes after the earthquake at 0445 UTC on 27 August 2012 (10:45 pm local time on August 26), and upgraded its advice to a tsunami warning for Central America countries at 0458 UTC as a precaution based on strong indications that this event was a slow "tsunami" earthquake.

Instrumental data recorded at sites in El Salvador showed a tsunami with 14 cm amplitude at Acajutla to the north at 12:10 am local time (0610 UTC) and no clear tsunami signal at La Union in the Gulf of Fonseca. There were, however, no gauges along coasts closest to the epicenter. The warning was cancelled at 0627 UTC when there was no expectation of new destructive impacts outside the area already potentially affected.

About 3 hours after the earthquake, sea level recordings from the Galapagos Islands showed a tsunami signal with amplitude of 40 cm. This indicated that a significant tsunami had been generated, even if its main impact was only localized near the epicenter. No reports came out of El Salvador in those first few hours of any damaging or destructive tsunami activity.

Within El Salvador however, there were reports of tsunami waves on the night of 26 August (local time) that were brought to the attention of government scientists at MARN (Ministerio del Medio Ambiente y Recursos Naturales) in San Salvador. On the basis of these reports, a preliminary survey was conducted in the field on 27 August by scientists from MARN. The preliminary survey established that a tsunami did occur and primarily affected the Peninsula of San Juan del Gozo, a sparsely populated area located directly shoreward of the epicenter. This survey also determined that there were no deaths caused by the tsunami but that there were several injuries caused by the wave.

2. EARTHQUAKE AND TSUNAMI

On 26 August 2012 at 10:37 pm local time (27 August, 2012, 0437 UTC), an earthquake with magnitude 7.3 (USGS) occurred off the coast of El Salvador. The earthquake epicenter as reported by the USGS was located some 100 km due south of the coast, in-line with the entrance to

Jiquilisco Bay (Figure 2.1). As shown in the regional bathymetry (GEBCO), the earthquake source region is in the vicinity of the Central America Trench where water depths range from 4000 to 5000m. The principal axis of a canyon-like bathymetric feature is oriented with the San Juan del Gozo Peninsula. Approximately 50 aftershocks with magnitudes between 4.2 and 5.5 occurred in the vicinity of the main event between 27 August 27 and 11 September 2012.

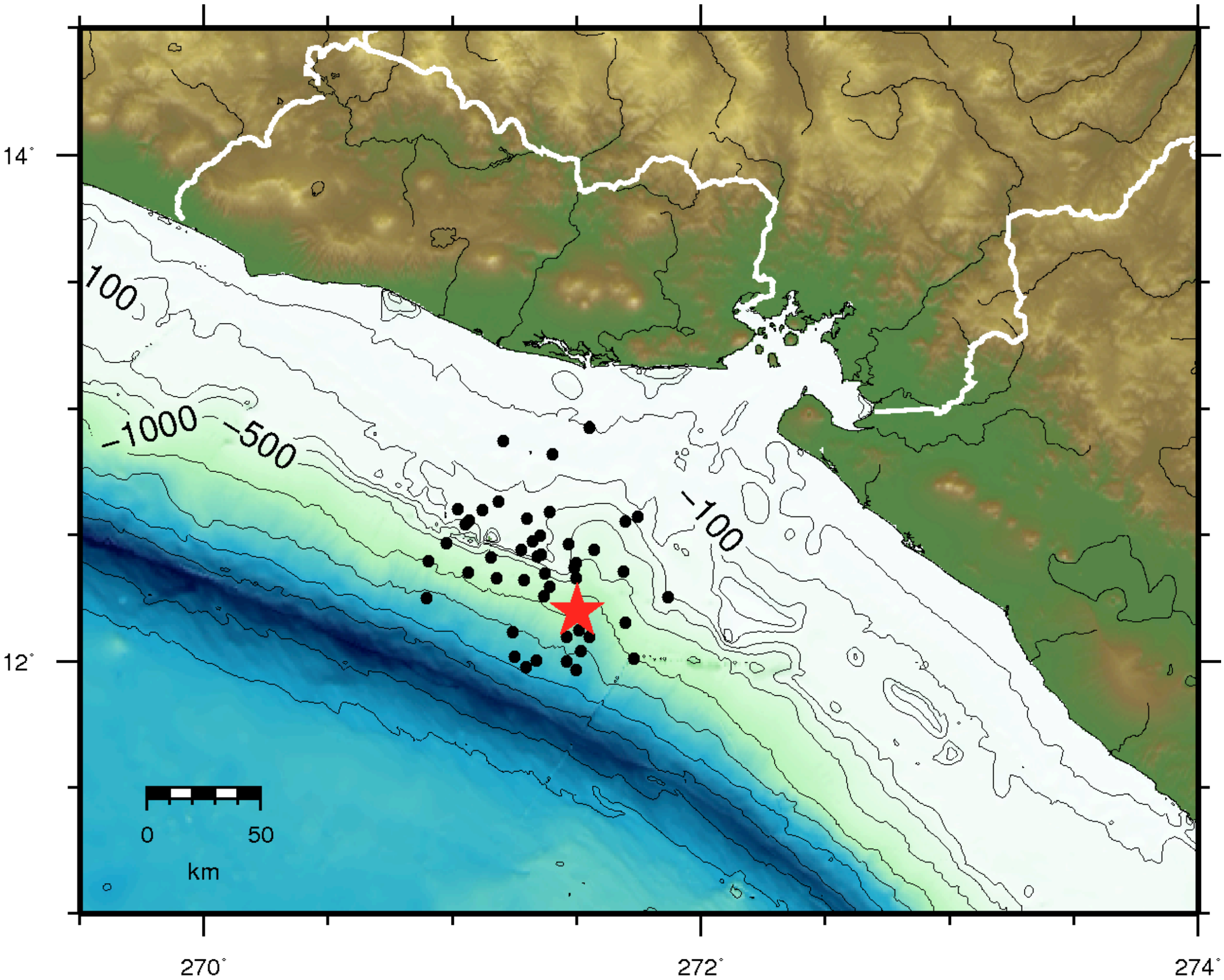

Figure 2.1 The Bathymetry offshore of El Salvador and Northern Nicaragua and the location of the USGS defined earthquake epicenter (red star). Black dots correspond to epicenters of aftershocks through 11 September, 2012. Contours labeled in meters.

The initial assessment of the earthquake by staff of the Pacific Tsunami Warning Center (PTWC) determined that the earthquake was significant due to the magnitude of the strength of the seismic signals and the long period nature of the initial seismic waves. Within 10 minutes of the main shock, additional analysis by the PTWC suggested that the earthquake could be characterized as a 'slow' earthquake. This was indicated by values (; Newman and Okal, 1998) in the range of -6.5 to -6.0 as computed by the PTWC. Typical values of for 'normal' thrust earthquakes are generally larger, in the range of -4.7. Additionally, values derived by the West Coast Alaska Tsunami Warning Center (WCATWC) were even lower at -7.0, further suggesting a very slow event.

Finally, analysis by the USGS finite fault method released in the days after the earthquake confirmed the slow nature and extended duration of the earthquake source, this is shown in the energy release function reproduced in Figure 2.2. This Figure shows that the energy released from this event occurred over a time period of approximately 70 seconds, which is quite long for an earthquake of that magnitude.

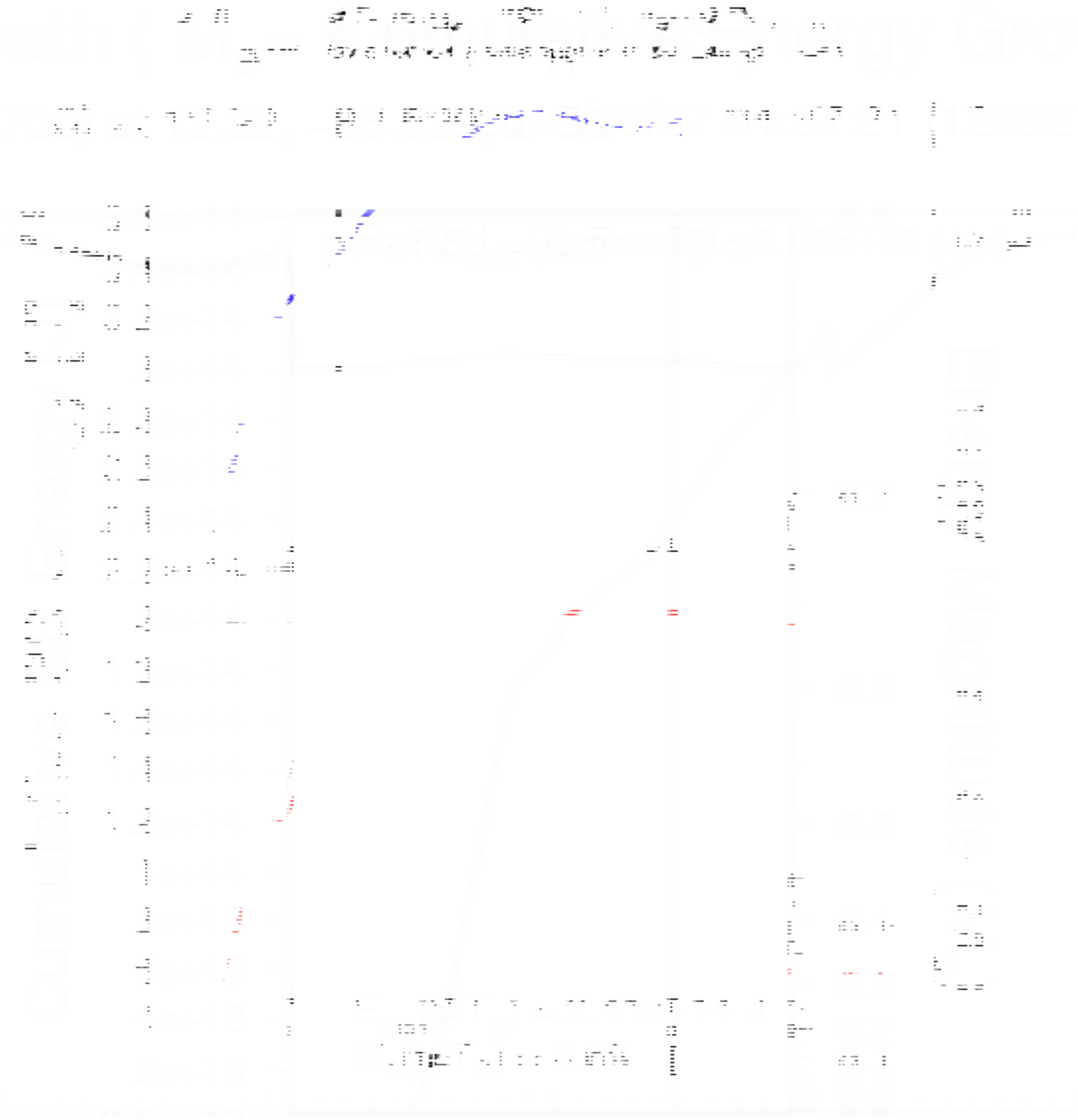

Figure 2.2 The preliminary energy-time relationships produced by the Real-Time Earthquake Energy and Rupture Duration Estimate project of the Georgia Institute of Technology and emailed to a distribution list approximately 10 minutes after the earthquake.

The tsunami was observed instrumentally on both near and far field water level recorders. In the near field the tsunami was observed on the Acajutla and La Union, El Salvador tide gauges. In the far-field, the tsunami was observed on tide gauges in the Galapagos Islands, La Libertad, Ecuador and on DART station 43413 (Table 2.1 and Figure 2.3 – 2.9).

Table 2.1 PTWC Summary of tide gauge recordings from the El Salvador tsunami.

Station	Country	Latitude	Longitude	arrival	P2T	Period
		(deg)	(deg)	(hrs)	(m)	mm:ss
Acajutla	El Salvador	13.57	-89.84	0:52	0.21	8:00
La Unión	El Salvador	13.31	-87.81	1:40	0.04	9:00
Baltra	Ecuador (Galápagos Island)	-0.44	-90.28	2:30	0.70	10:00
Santa Cruz	Ecuador (Galápagos Island)	-0.72	-90.31	2:49	0.39	13:20
La Libertad	Ecuador	-2.22	-80.91	3:36	0.37	11:30
DART 43413	n/a	10.84	-100.08	1:36	0.02	8:00

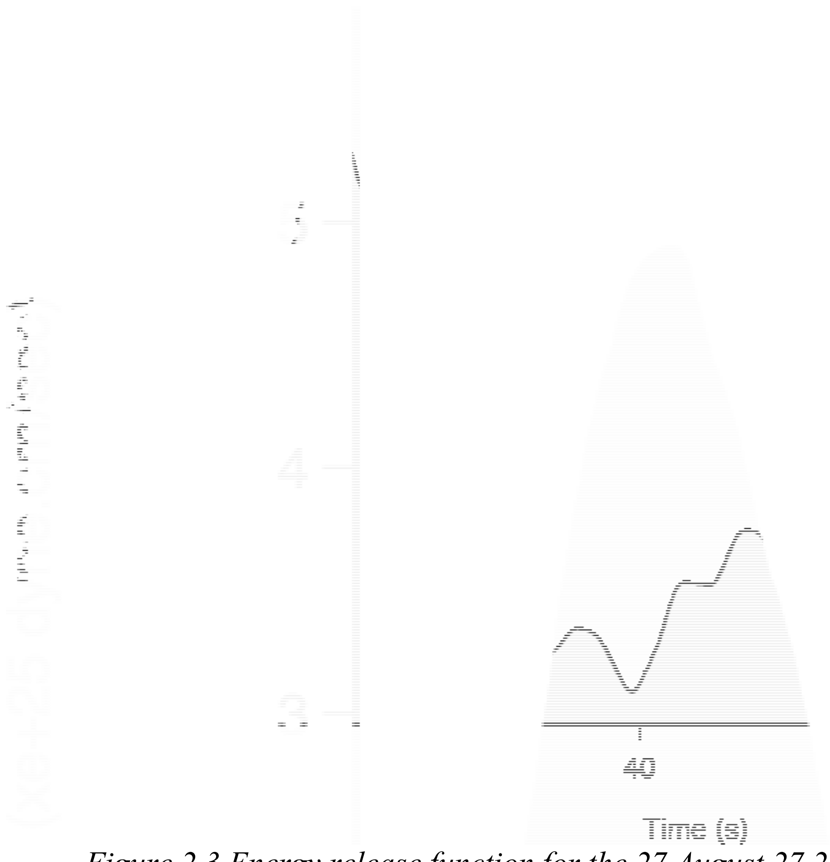

Figure 2.3 Energy release function for the 27 August 27 2012 El Salvador earthquake (Mw 7.3). Energy release occurs over 70 seconds.

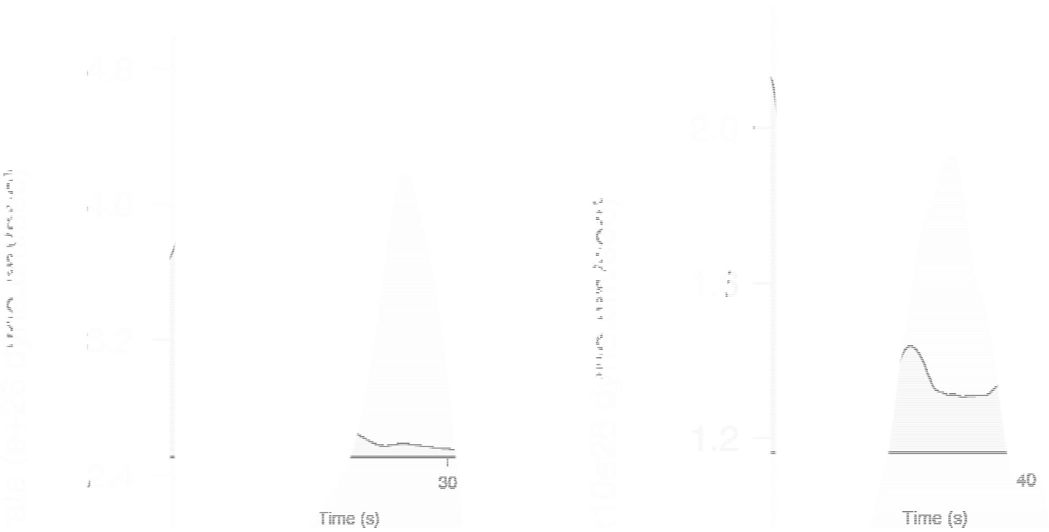

Figure 2.4 Energy release functions for the 31 August 2012 Philippines earthquake (Mw 7.6, left) and the 5 September 2012 Costas Rica Earthquake (Mw 7.6, right). Note that although both of these are larger in terms of magnitude, the energy is released in less time than in the El Salvador event, particularly in the case of the Philippines event.

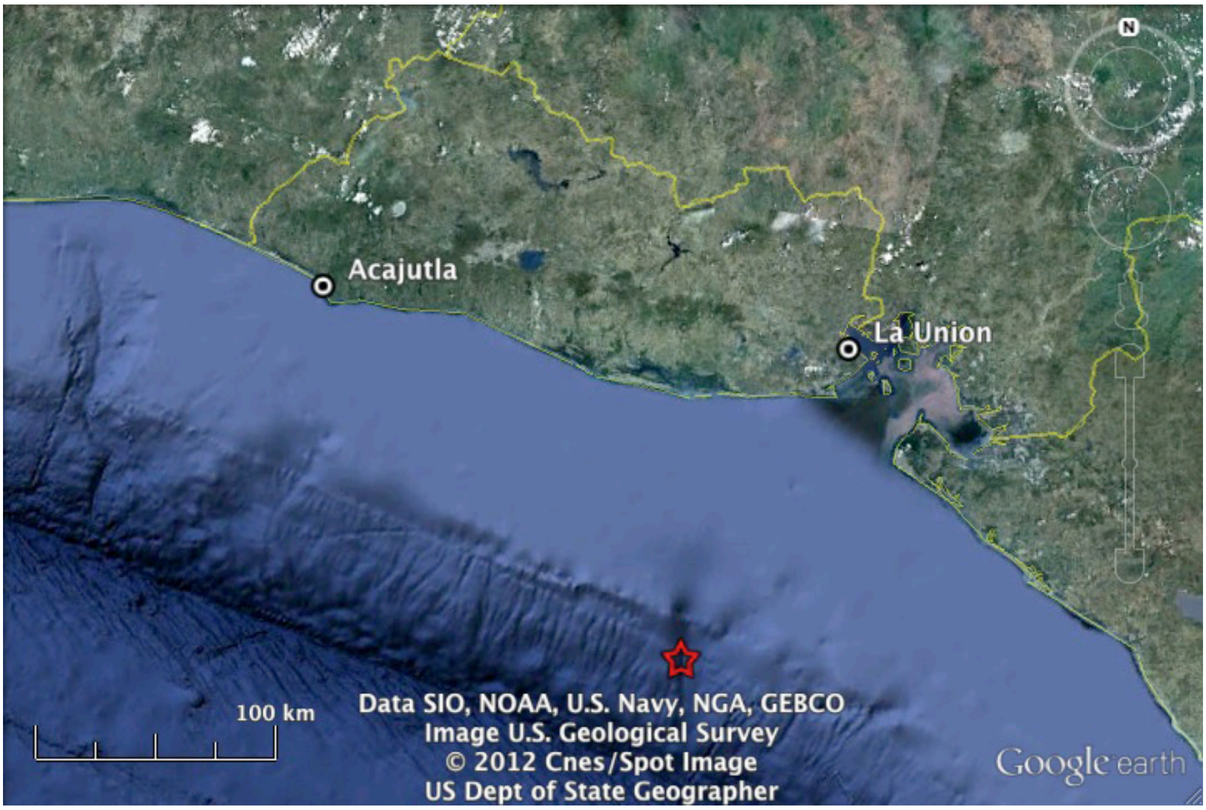

Figure 2.5 Locations of the two tide stations in El Salvador that recorded the August 26th, 2012 tsunami. The earthquake source location is indicated with the red star.

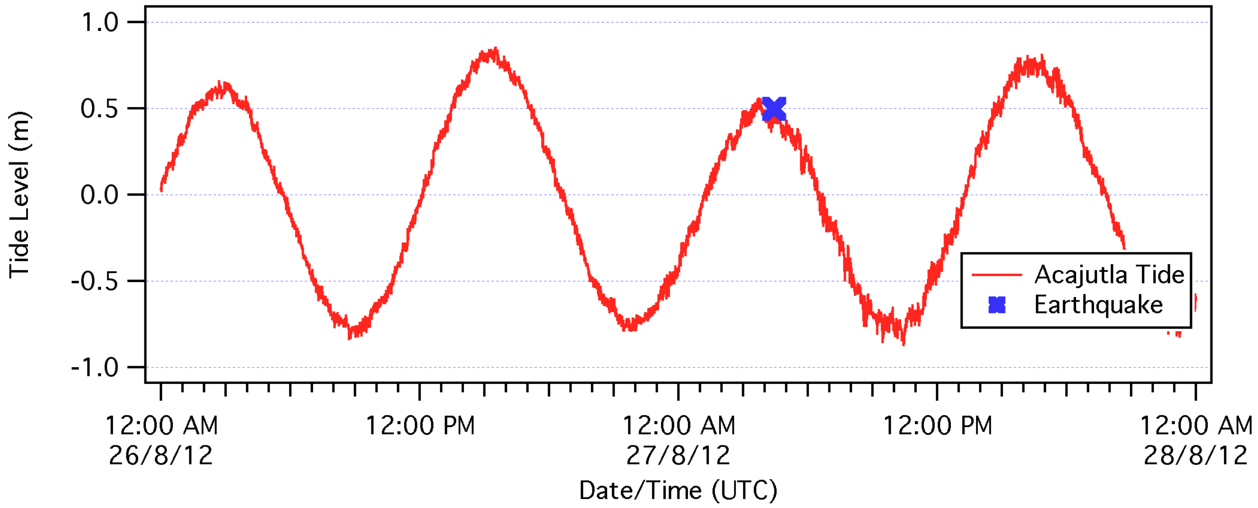

Figure 2.6 Acajutla tide gauge data from the time of the earthquake.

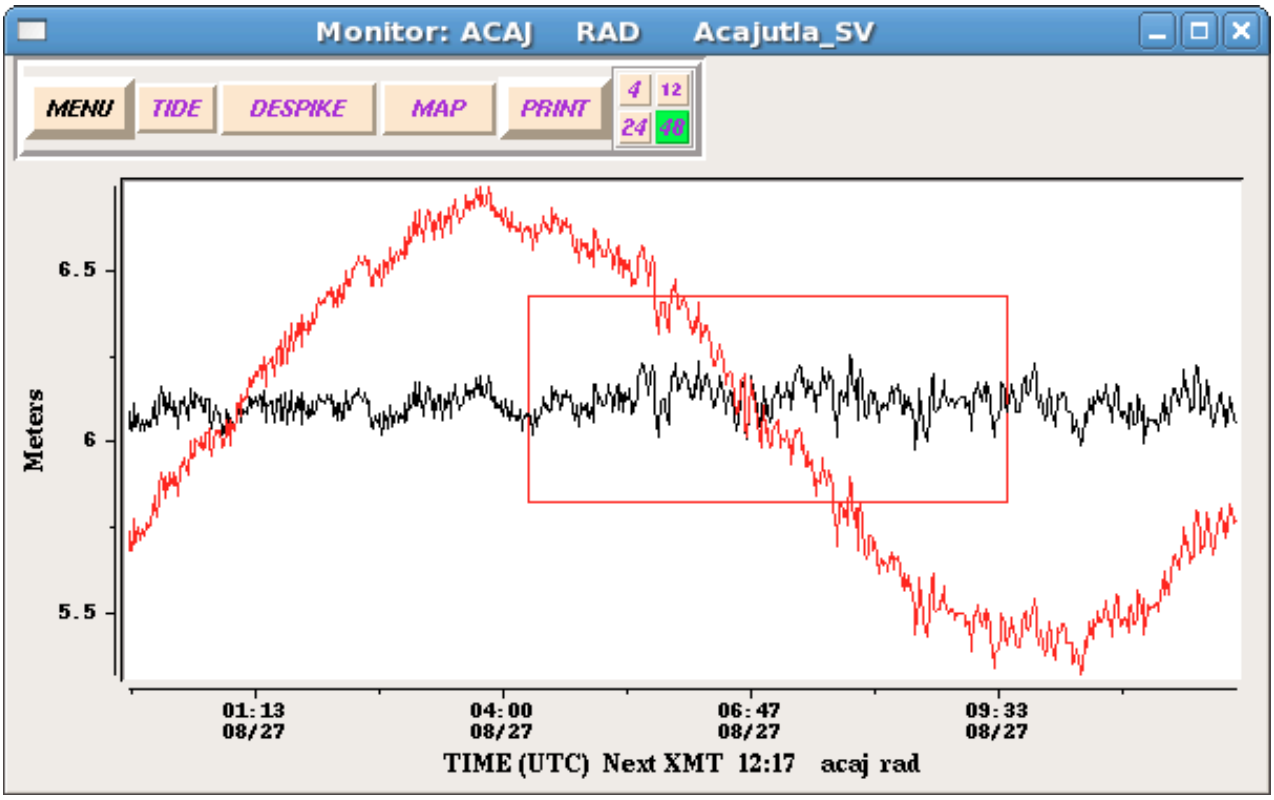

Figure 2.7 PTWC plot of the El Salvador tsunami on the Acajutla, El Salvador tide gauge.

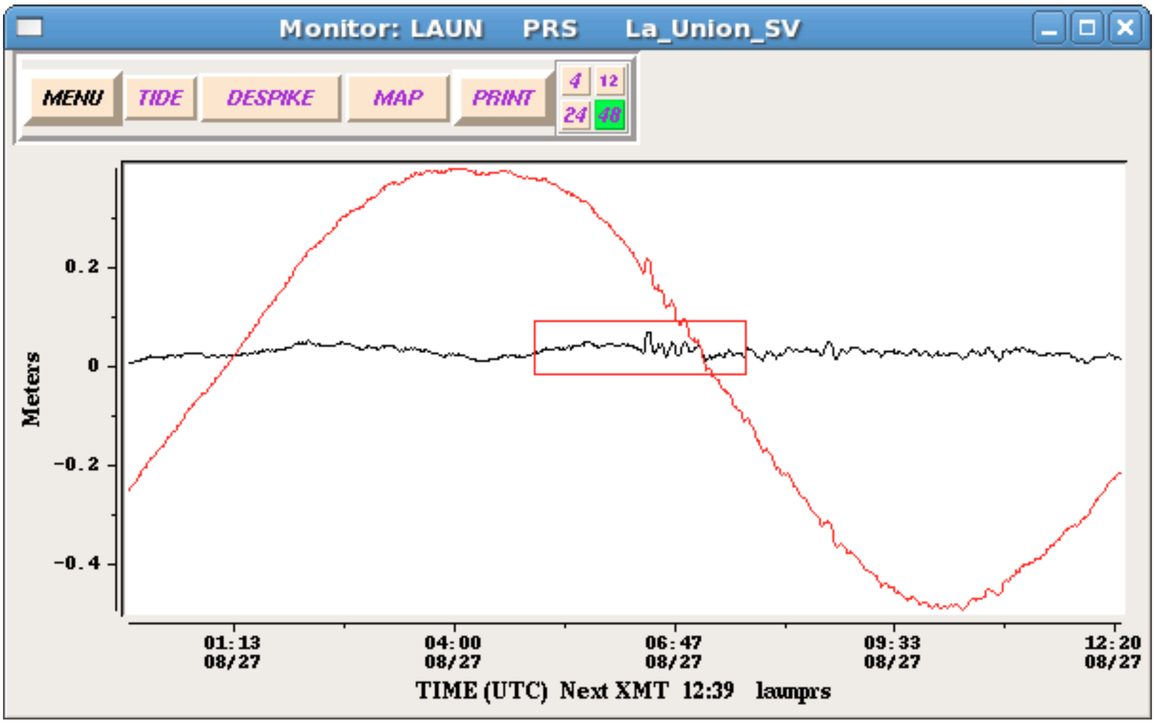

Figure 2.8 PTWC plot of the El Salvador tsunami on the La Union, El Salvador tide gauge.

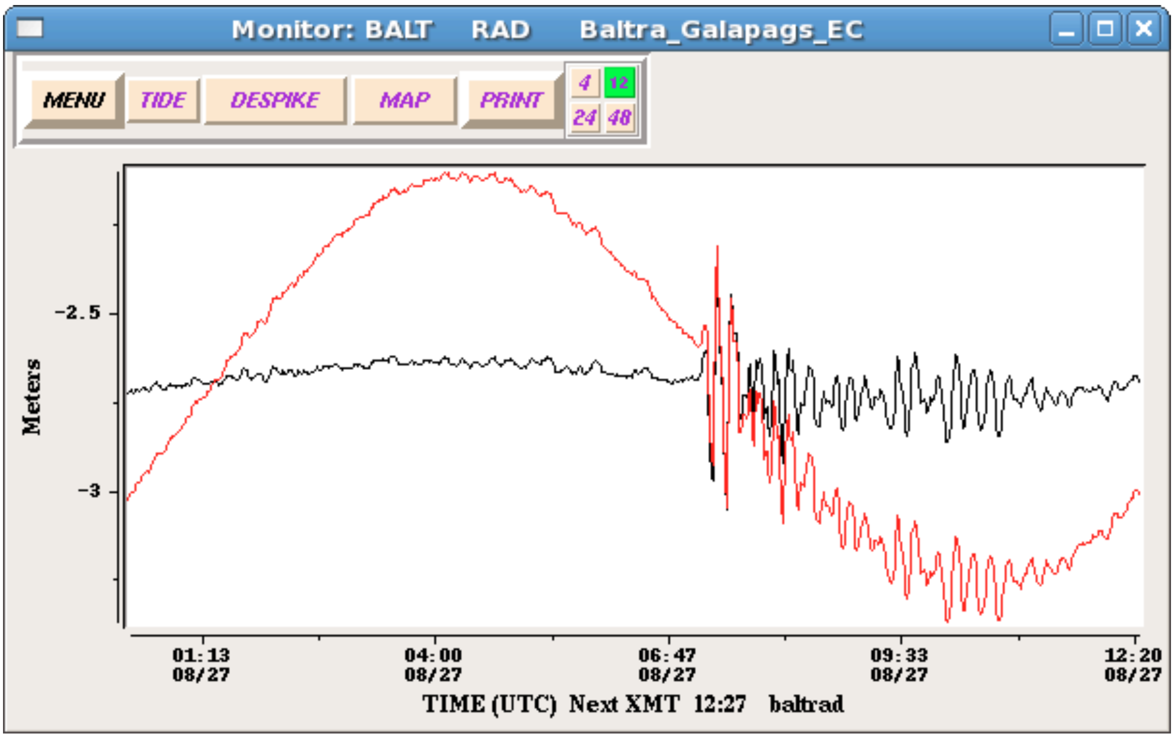

Figure 2.9 PTWC plot of the El Salvador tsunami on the Baltra, Galapagos Islands tide gauge. The gauge is located ~1400 km away along a 191° path.

Due to the location of the earthquake and the fact that tsunamis radiate the majority of their wave energy perpendicular to the axis of the fault plane, neither of the El Salvador gauges were ideally located to receive the tsunami signal. Furthermore, Acajutla is located on the far side of a large headland while La Union is located several kilometers from the open ocean in the Gulf of Fonseca. In contrast, the Galapagos Islands are nearly ideally located to receive a strong signal from this event. Although they are approximately 1400 km away, they are located on a 190° path (S) from the source region, just 15° off of the trench perpendicular direction of 205° path (SSW), and favorably situated for energy focusing by the Cocos Ridge. As a result the two stations in the Galapagos (Baltra and Santa Cruz) recorded a very strong, clear tsunami signal that arrived some 2.5 hours after the earthquake. Following the initial wave packet, both stations also responded with a secondary (and in the case of Santa Cruz tertiary) wave packet with amplitudes nearly as large as the initial wave. A similar extended duration and resurgence of wave height was also observed on these stations during the March 11, 2011 Tohoku tsunami (Lynett et al., 2012).

Further off axis, were DART 43413, approximately 1200 km away at 265° path (W), and the La Libertad, Ecuador station, approximately 1800 km away at 155° path (SSE). Evident in the DART record is the high frequency signal from the earthquake followed ~1.5 hours later by a single tsunami wave pulse with a peak to trough (P2T) height of 0.024 m. The La Libertad signal is characterized by long period non-tsunami oscillations present before the tsunami arrival. The tsunami itself appears clearly some 3.5 hours after the earthquake, with the largest signal occurring some 5 hours after the tsunami arrival.

Within days of the event preliminary hydrodynamic models of the tsunami had become available. Results from the MOST tsunami model (Titov and Gonzalez, 1997) are presented in Figure 2.10 (Nikos Kalligeris, pers. comm.). For this simulation, the model was initialized using the USGS finite fault solution for the slip distribution. The finite fault solution describes a distributed slip distribution across the source area with a maximum slip amount on the order of 1 m. While the model result shows strong focusing of wave energy towards the western end of the San Juan del Gozo peninsula, the absolute wave heights are somewhat deficient to have caused the reported 5 m tsunami heights in that area. The model also shows some focusing of wave energy towards the east in to northern Nicaragua and corresponding with areas that reported some tsunami effects.

The fact that the direct application of the USGS Finite Fault model as the initial condition for the tsunami hydrodynamic yields results deficient in wave heights necessary to explain the reported effects should not come as a surprise. Indeed, in the case of the October 2010 Mentawai earthquake and tsunami, hydrodynamic simulations initialized with a direct application of the finite-fault slip amounts also severely under predicted the observed wave heights (Hill et al., 2012). In order to match the observed wave effects, it was necessary to scale the slip amounts by an average value of 5.6 (Newman et al., 2011). The necessity for this scaling factor was attributed to the slow, shallow nature of the earthquake rupture and the correspondingly lower shear wave velocities encountered in the shallower portions of the earth's crust (Newman et al., 2011).

3. TSUNAMI FIELD SURVEY

An initial survey was conducted by representatives of MARN, the Salvadorean Ministry for the Environment and Natural Resources (Ministerio del Medio Ambiente y Recursos Naturales) in the days immediately following the event (on 27 – 29 August 2012). This survey focused on attending to the immediate needs and disseminating factual information to the affected population. A number of interviews were recorded from eyewitnesses.

Following the organization of the International Tsunami Survey Team (ITST), a second survey visited the affected areas on 5-7 September 2012. The survey team visited 11 separate sites throughout the affected area. These sites are depicted in Figure 3.1.

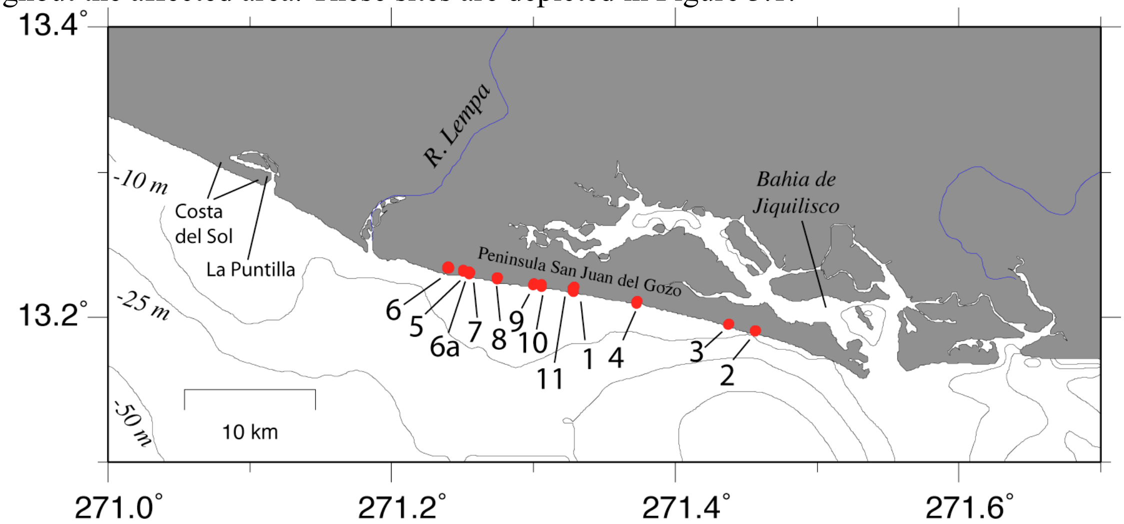

Figure 3.1 Survey sites along the San Juan del Gozo peninsula.

The survey focused on the San Juan del Gozo Peninsula where the strongest tsunami effects were observed. At each of the 11 sites one or more measurements of tsunami height, runup, flow direction and inundation distance were recorded using established protocols (Synolakis and Okal, 2002, Dominey-Howes et al., 2012). Watermarks were surveyed with a Trimble GPS rover connected via Bluetooth to a laser range finder (Lasercraft XLRic) to record offset points and differentially corrected during post-processing with the base station network of UNAVCO. Measured data are presented relative to the tide level at the time of tsunami arrival.

Table 3.1 Survey site names corresponding to numbers in Figure 3.1.

Number	Site Name (closest town or between towns)
01	La Maroma
02	Corral de Mulas (1)
03	Corral de Mulas (2)
04	El Retiro
05	Isla de Méndez (1)
06	Montecristo mangrove
6a	Isla de Méndez (2)
07	Isla de Méndez (3)
08	San Juan del Gozo lagoon
09	Ceiba Doblada (1)
10	Ceiba Doblada (2)
11	Ceiba Doblada (3)

The definitions of reference water level, inundation distance, flow depth, tsunami height and run-up height are as follows:

1. Reference water level: Is the tide level at the time of tsunami arrival.
2. Inundation distance: Is the horizontal distance wetted by the tsunami flow.
3. Flow depth: Is the depth of the tsunami surge above the ground as indicated by flow markers.1
4. Tsunami height: Is the sum of flow depth and the local topographic height.

(Flow markers: piles of debris; impact scars on tree trunks; bark stripped from trees; mud marks on the walls of buildings).

4. RUN-UP HEIGHT ABOVE SEA LEVEL REACHED BY THE TSUNAMI AT THE POINT OF MAXIMUM INUNDATION.

All of the sites surveyed in El Salvador were located on the San Juan del Gozo peninsula which separates Jiquilisco Bay from the Pacific Ocean. In total 11 sites were surveyed as indicated in Figure 3.1. All of the sites were very similar in terms of the geomorphology characterized by a relatively steep, dark sand beach face, with a dune crest at the top of the beach berm. Landward of the beach berm the terrain was either level or sloping slightly downward. The vegetation was comprised of low beach plants, sea grape (icacos) plants, grasses and spiny cactus type plants. There were very few tall trees only at the western extreme of the peninsula (Montecristo mangrove).

Site 01: La Maroma.

It is name of the town nearest of a section of the beach along the San Juan del Gozo Peninsula. It was in this area however where the most people were affected by the tsunami and the strongest effects were observed. This area is also the site of one of larger sea turtle hatcheries (vivero) in the area.

Ofilio Herrera, MARN and Civil Protecion, indicated that the peninsula lacked high ground to evacuate to, and few means of transportation for moving inland. Mr. Herrera said communities on peninsula did not receive any tsunami alert prior to the arrival of the tsunami.

We were met at site by the municipal Mayor (Alcalde), Mr. Rigoberto Herrera Cruz. He was accompanied by several representatives from the local Civil Protection group and turtle hatchery workers.

The site featured a small shed (ramada) with wood posts and the walls and roof made from aluminum siding (lamina) located next to the hatchery. The hatchery itself is a simple structure comprised of perimeter fence with concrete posts. Wooden posts supported a simple roof made of palm fronds for shade.

During the tsunami, the walls of the ramada were torn off of the posts that are deeply embedded in the sand. The posts themselves were not pulled out of the ground, but some were leaned over by the force of the water. By the time of the survey the ramada had been repaired and had new walls and roof.

A worker at the hatchery, Jose Barrera-Garcia, was in the ramada as the tsunami struck and came out when he heard people crying out. He was dragged some 90 m by the wave from the ramada to a tree, where he was suspended in tree branch. The height of the branch was measured at ~2.1 m above ground. Mr. Barrera-Garcia reported that he saw three waves, however we suspect there is some confusion in differentiating between wind and tsunamis waves. Mr. Barrera-Garcia said it took 20 minutes for water to recede and fully drain. He said flow depth reached just beneath the roof of the ramada as indicated in Figure 3.5. At maximum inundation extent observed (340 m) by Mr. Garcia, he said less than 1 m water depth.

Figure 3.5 Jose Barrera-Garcia at the newly rebuilt ramada. Mr. Barrera-Garcia was swept away by the tsunami and suffered minor injuries. The tsunami flow depth at this location was reported by Mr. Barrera-Garcia to be over 2 m.

Jose Fermin Piñeda, 25 years old, from Isla de Mendez, was on the beach when the tsunami arrived. He had just delivered a turtle to the hatchery. He was standing just outside the shed that Jose Barrera- Garcia was sitting in. He also described 3 waves, the first of which carried him beyond the tree that Jose Barrera was caught in, near the bushes.

Jose Gabriel Chavez, local coordinator for Civil Protection, said he was inland and felt the earthquake describing it like he was in a swaying boat. He felt the swaying for 30-40 seconds. He said when he arrived at the impacted area (turtle hatchery referenced above) he found ~40 people injured, 3 of which are still in hospital. He also described gurgling noises (water draining into sand) on the beach area.

Jose Maria Argueta, local Civil Protection worker and member of local NGO Asociación Mangle that is working with Save the Children a USAID/OFDA-funded disaster risk management project, said that at the organizational level the Civil Protection personnel had basic tsunami knowledge but needed more support and training. Training by the project has covered first aid and early warning for flooding events up to now. Mr. Arqueta indicated the local population had no knowledge about tsunamis and did not know it was a hazard in their area. Mr. Arqueta stated that no one in Isla de Mendez received a tsunami alert, but that the community passed the information about the wave(s) up the chain to the next level, which was the municipality of Jiquilisco.
Site 02: Corral de Mulas (1).

After Isla de Mendez the team moved towards the eastern end of the Gozo Peninsula, stopping at three locations while driving along the beach dunes. At the first site we spoke with Jaime Enrique Mejia, a worker at turtle hatchery who was not at site at time of event. However, he showed us debris (tree trunk and palms) that were deposited just in front of a hut used by workers. The hut was not impacted. At the time of the earthquake, Mr. Mejia was inland and reported that he felt the earthquake, which he described as light ('leve' in Spanish). He reported that light fixtures hanging from the ceiling swayed during earthquake and that corrugated sheet metal ("lamina") used for walls and roofing vibrated strongly.

Site 03: Corral de Mulas (2).

Francisco Esteban Elena Aguilar, turtle hatchery worker said that the shaking lasted 2-3 minutes. He describes two waves, second being the largest. Aguilar mentioned his goods and personal items stored in the hut were lost. He also mentioned that water reached the top of nearby fence post, measured at ~1 m higher than the dune crest and a few meters inland.

Site 04: El Retiro

No witnesses were encountered at El Retiro, however a resident of the area working with the survey team (Mr. Ofilio Herrera) reported that at this location a child as well as a man and a horse were dragged down the beach by the wave. At this site the team encountered evidence of tsunami over-wash and inundation.

Site 05, 06, 6a, 07: Isla de Mendez (1), (2), (3) and Montecristo mangrove.

Montecristo mangrove is located to the west of Isla De Mendez (see Figure 3.1). This marks the beginning of a forest of tall mangroves that extends approximately 6 km to the west towards the mouth of the Rio Lempa. The mangroves at the shoreline are dying off as evidenced by the brown color and seen in overhead images. The exact cause of the mangroves dying off is not known, however it is a slow, ongoing process and is not related to the tsunami.

Witness Evan Antonio Coronel was sitting near the shed area at the time of wave arrival. He described three waves, the third of which carried him inland. Mr Coronel indicated the furthest inundation point, ~150 m from the shoreline. His testimony of the effects indicated a maximum of ~4.5m flow depth. He also indicated a loud noise preceding wave arrival which he described as like a loud bus. Another local resident, Carlos Antonio mentioned that there were approximately 50 people working on that part of the beach on the night of the tsunami. He himself was in the community of San Juan del Gozo lagoon that evening, and didn't feel the tremor. They did not receive a warning. He said that 6 turtle nests were lost. From this location, the survey team walked approximately 1 km further west to the edge of the dead mangrove forest. In this area there was evidence of tsunami inundation. A run-up point and inundation distance were measured.

Site 08, 09, 10, 11: Ceiba Doblada (1), (2), (3) and San Juan del Gozo lagoon.

Driving eastward towards Ceiba Doblada, the team stopped at several sites where there was clear evidence of tsunami inundation. There were no residents or locals in the area available for interviews. At these sites the teams measured run-up and inundation and documented the evidence of the tsunami (Figure 3.26 through Figure 3.28).

Figure 3.26 Tsunami debris line.

Figure 3.27 Tsunami debris line.

Figure 3.28 Dead vegetation from salt water intrusion.

During the helicopter over flight of the following day, several aerial images of this area were recorded (Figure 3.29 and Figure 3.30).

Figure 3.29 Aerial view of a tsunami debris line.

Figure 3.30 Aerial view of sand deposits from tsunami overwash.

To the west of the study area is a popular and highly developed beach resort area known as Costa del Sol (see Figure 3.1). At the eastern end of this area is a grouping of restaurants built directly on the water front. Indeed some of the restaurants have seating areas set directly over the water (Figure 3.31 and Figure 3.32). Given the extremely vulnerable location of these structures, it could reasonable by expected that if a tsunami wave the same size as that which affected Isla de Mendez hit this area, there would have been reports of significant effects or damage.

Figure 3.31 La Puntilla.

Figure 3.32 La Puntilla.

During the initial survey immediately after the earthquake and tsunami conducted by MARN, residents and proprietors here did not report any such effects, nor was any evidence observed supporting that notion. Only at the isla Tasajera, between Costa del Sol and rio Lempa, the turtle hatchery workers report that they hear something unusual coming from the sea, but no evidence of the tsunami was find it.

Just to the west of La Puntilla is the popular resort area of Costa del Sol (Figure 3.33 through Figure 3.35).

Figure 3.33 Costa del Sol.

Figure 3.34 Costa del Sol.

Figure 3.35 Aerial view towards La Puntilla and Costa del Sol to the west.

As seen in the aerial images, the area is very developed with numerous structures built close to shore and many potential witnesses in the area on the night of the tsunami. During the preliminary MARN survey, there were no reports from this area of inundation, damage or effects, again suggesting that the tsunami here was very small.

The preliminary MARN survey received reports from several other areas around El Salvador regarding the tsunami.

At the Port of Acajutla, there were no observations of sea level changes and ships moored in the port did not experience any unusual surges. We note that a surge of 0.2 m with an 8 minute period was recorded on the Acajutla tide gauge (Table 2.2). Workers at the port maintained their normal shifts, however they were alerted to the possibility of tsunami effects that night by MARN.

Playa El Espino is located to the east of the entrance to Jiquilisco Bay. Resident and president of the local Restaurants Association Mrs. Blanca Yorahimi Larreynaga was interviewed by telephone on the morning after the tsunami. She reported that there were no observable tsunami effects and that the local police had moved into the peninsula of St. Juan del Gozo to help assist people affected in that area.

Playa El Cuco is located well to the east of the Bay of Jiquilisco. A phone call was placed to the administrators of the Hotel Las Flores, a popular surfing resort for North Americans. They reported that on the night of the tsunami there were no unusual events. The local surf guide and boat captain said that the boats left parked on the beach were not moved or disturbed in any way and that activities of the next day resumed normally.

The data collected by the El Salvador survey team is summarized in Figure 3.32, Table 3.2 and Table 3.3. The data are divided into flow depths, tsunami heights and runup heights as defined in Figure 3.3. Because the topography landward of the dune ridge sloped downward, runup heights are generally lower than the maximum tsunami heights.

Table 3.2 Run-up measurements from the 2012 El Salvador tsunami.

Date	Time	Latitude	Longitude	Run-up*	Watermark	Description
	UTC-6	North	East	(m)		Eyewitness confirmed
5-sep-2012	12:05:34	13.221	-88.671	2.20	Wrack Line	Yes
5-sep-2012	15:15:09	13.191	-88.543	5.35	Wrack Line	On top of dune tree log
5-sep-2012	15:46:52	13.195	-88.562	3.69	Wrack Line	Brown grass
5-sep-2012	16:38:15	13.211	-88.627	1.66	Wrack Line	Yes
6-sep-2012	08:32:22	13.232	-88.749	2.08	Wrack Line	Brown vegetation
6-sep-2012	08:56:52	13.232	-88.749	2.30	Wrack Line	Brown vegetation
6-sep-2012	10:01:02	13.235	-88.760	2.14	Wrack Line	Embankment next to mangrove
6-sep-2012	10:06:42	13.235	-88.760	1.91	Wrack Line	Next to mangrove
6-sep-2012	10:54:07	13.231	-88.745	3.51	Wrack Line	Field next to fence
6-sep-2012	10:58:39	13.231	-88.745	3.50	Wrack Line	Field next to fence
6-sep-2012	11:18:21	13.227	-88.725	3.30	Wrack Line	Field next to fence
6-sep-2012	11:24:57	13.227	-88.725	3.07	Wrack Line	Brown vegetation
6-sep-2012	12:27:27	13.223	-88.700	3.22	Wrack Line	Brown vegetation
6-sep-2012	12:47:18	13.223	-88.694	2.07	Wrack Line	Brown vegetation
6-sep-2012	13:03:53	13.220	-88.672	3.17	Wrack Line	Brown vegetation

*The run-up average was 2.88 m.

Date	Time	Latitude	Longitude	Terrain	Flow depth	Tsunami height*	Watermark	Description
	UTC-6	North	East	(m)	(m)	(m)		Eyewitness confirmed
5-sep-2012	11:42:07	13.218	-88.672	4.22	2.1	6.32	Mud line inside	House pole
5-sep-2012	11:53:35	13.219	-88.672	3.54	2.3	5.84	Broken branch	Wrapped in sheet metal
5-sep-2012	15:51:40	13.195	-88.562	5.13	0.5	5.63	Dune overtopped	Yes
5-sep-2012	16:34:33	13.210	-88.627	3.97	0.5	4.47	Damage trim line	Wooden palm leef hut
6-sep-2012	08:26:22	13.232	-88.749	3.25	1.6	4.85	Damage trim line	Hut with sheet metal
6-sep-2012	08:48:35	13.232	-88.749	3.29	1.6	4.89	Damage trim line	House siding
6-sep-2012	09:14:16	13.232	-88.749	2.19	0.5	2.69	Raft debris	Debris in fence
6-sep-2012	09:46:06	13.234	-88.759	3.55	0.6	4.15	Damage trim line	Hut with sheet metal
6-sep-2012	10:59:56	13.231	-88.746	3.19	1.6	4.79	Broken branch	Tree on top of dune

*The tsunami height average was 4.85 m.

4. SUMMARY, FINDINGS AND NEXT STEPS

A tsunami was generated by the 26 August 26 2012, magnitude (Mw) 7.4 earthquake centered offshore of south eastern El Salvador. The causative earthquake was a 'slow earthquake', a type of earthquake known to cause tsunamis disproportionally higher than the earthquake magnitude alone would suggest. The tsunami generated by the earthquake primarily affected approximately 30 km of the El Salvador coastline directly landward of the earthquake epicenter.

The strongest tsunami effects were observed along the beaches of the San Juan del Gozo peninsula which runs eastward from the mouth of the Lempa River and separates Jiquilisco Bay from the Pacific Ocean. Peak tsunami heights were measured up to 6 m at Isla de Mendez with tsunami heights of 3 to 6 m measured approximately 15 km west and east of this location. The tsunami caused inundation of up to 350 m inland at Isla de Mendez. Tsunami heights were relatively uniform across the survey area. Coastal areas 25 km to the west (i.e. Costa del Sol) were not affected by damaging tsunami waves, nor were areas just to the east, suggesting relatively localized effects.

In addition to the Field Survey, ITST team members were also requested to provide advice to MARN on how to strengthen its national tsunami warning and mitigation system. The observations and findings from the ITST team were supplemented with advice from Directors of the Pacific Tsunami Warning Center and International Tsunami Information Center, and the Technical Secretary of the ICG/PTWS. The findings should be considered preliminary. Further detailed discussions with subject matter experts will be necessary to develop action plans that can lead to robust and reliable improvement to El Salvador's tsunami warning and mitigation system. The overall findings were as follows:

1. The 26 August 2012 earthquake highlighted the insufficiency of current El Salvador seismic resources to rapidly and accurately determine the magnitude of a great earthquake in time to identify the risk of an impending tsunami and allow authorities to act on that information. Denser national and regional seismic networks and quick magnitude estimation techniques will be required for timely local earthquake source characterization. In the interim, MARN may want to utilize the PTWC Earthquake Observatory Message as a first indicator of earthquake size.

2. MARN should review of their existing tsunami alert and warning protocols, particularly for near-field events. For local tsunamis and immediate alert dissemination in minutes, warnings should be based solely on earthquake information since seismic signals are currently the fastest early tsunami warning signals.

3. To determine the severity and longevity of dangerous tsunami waves, real or near-real time monitoring of sea levels is required. Currently, El Salvador has 2 working coastal sea level stations and Nicaragua 1 coastal sea level station. More are required, especially facing the open ocean, and should be given highest priority as the most economical means of confirming tsunamis. Actual observations, whether by coastal or deep-ocean sensors, along with eyewitness reports by local authorities, are essential for determining when to cancel tsunami warnings, and when it is safe for the public to return to the evacuated area.

4. At present, local tsunami wave forecasting must utilize database-driven pre-calculated tsunami scenarios. In general, near real-time data, whether by DART systems or coastal gauges, are too late to be used as input to local tsunami wave forecasting. Deployment of a deep-ocean sensor off El Salvador will be of most use to countries around the Pacific monitoring a Central America source as a distant tsunami that might impact them.

5. To enable communities to better respond to local tsunamis, they must know their tsunami hazard and what to do. Development of tsunami inundation maps and evacuation zones for at-risk areas of El Salvador will assist greatly. Additionally, outreach and education are essential activities. Place emphasis on the recognition of a tsunami's natural warnings signs as a key local tsunami preparedness message. Development and mainstreaming tsunami preparedness into school curricula will ensure sustainability over generations.

6. Civil Protection should develop tsunami response plan at the national level, as well as the local level. Response plans should document agencies, protocols, and standard operating procedures to enable rapid and seamless warning communication and evacuation of vulnerable communities, followed by immediate disaster response to save lives.

7. To focus on the tsunami hazard, a national-level tsunami coordination committee comprised of key stakeholder agencies should be formed to regularly meet to discuss, agree, and oversee the development on sustainable, effective end-to-end warning system. Topics should include (1) hazard risk assessment, (2) warning, (3) emergency response, and (4) preparedness and mitigation.

8. Identify a sustainable source for tsunami information and technical assistance. Technical assistance on (1) hazard risk assessment, (2) warning, (3) emergency response, and (4) preparedness and mitigation is available from several sources including but not limited to technical cooperation agencies like JICA, GIZ, USAID, or others, intergovernmental mechanisms like the ICG/PTWS and its International Tsunami Information Center ITIC and from UN agencies like UNDP, UNESCO and ISDR. These should be considered as subsidiary to internal capacities El Salvador is trying to develop to address and mitigate tsunami risk.

5. REFERENCES

Abe, K., Tsuji, Y., Imamura, F., Katao, H., Iio, Y., Satake, K., Bourgeois, J., Noguera, E., and Estrada, F. (1993) Field Survey of the Nicaragua Earthquake and Tsunami of September 2, 1992, Bulletin of the Earthquake Research Institute of the University of Tokyo (in Japanese), 68, 23-70.

Dominey-Howes, D., Dengler, L., Dunbar, P., Kong, L., Fritz, H., Imamura, F., McAdoo, B., Satake, K., Yalciner, A., Yamamoto, M., Yulianto, E., Koshimura, S., and Borrero, J. (2012). International Tsunami Survey Team (ITST) Post- Tsunami Survey Field Guide. 2nd Edition. UNESCO-IOC, Paris.

Gica E.M., Spillane, M., Titov, V.V., Chamberlin, C., and Newman, J.C. (2008) Development of the forecast propagation of the forecast propagation database for NOAA’s Short-term Inundation Forecast for Tsunamis (SIFT), NOAA Tech. Memo OAR PMEL-139, 89 pp.

Hill, E, Borrero, J., Huang, Z., Qiu, Q., Banerjee, P., Natawidjaja, D., Elosegui, P., Fritz, H., Pranantyo, I., Li, L., Macpherson, K., Skanavis, V., Synolakis, C., and Sieh, K. (2012) The 2010 Mw 7.8 Mentawai earthquake: Very shallow source of a rare tsunami earthquake determined from tsunami field survey and near-field GPS. Journal of Geophysical Research, Vol 117, B06402, doi:10.1029/2012JB009159.

Kanamori, H. (1972) Mechanism of tsunami earthquakes, Phys. Earth Planet. Int., 6, 346-359.
Polet, J. and Kanamori, H. (2000) Shallow subduction zone earthquakes and their tsunamigenic potential, Geophys. J. Int., 142, 684-702.

Kanamori, H. and Kikuchi, M. (1993) The 1992 Nicaragua earthquake: a slow tsunami earthquake associated with subducted sediments. Nature, 361, 714- 716.

Newman, A.V., and Okal, E.A. (1998) Teleseismic estimates of radiated seismic energy: The E/M0 discriminant for tsunami earthquakes, J. Geophys. Res., 103, 26885-26898.

Newman, A. V., G. Hayes, Y. Wei, and J. Convers (2011), The 25 October 2010 Mentawai tsunami earthquake, from real-time discriminants, finite- fault rupture, and tsunami excitation, Geophys. Res. Lett., 38, L05302, doi:10.1029/2010GL046498.

Satake, K., Bourgeois, J., Abe, K., Abe, K., Tsuji, Y., Immura, F., Iio, Y., Katao, H., Noguera, E., and Estrada, F. Tsunami Field Survey of the 1992 Nicaragua Earthquake, Eos: Trans. Am. Geophys. Un. 74,13, pp145, 156-157.

Synolakis, C.E. & Okal, E.A., 2005. 1992–2002: Perspective on a decade of posttsunami surveys, in: Tsunamis: Case studies and recent develop- ments, ed. K. Satake, Adv. Nat. Technol. Hazards, 23:1–30.

Titov, V., and F. I. González (1997), Implementation and testing of the Method of Splitting Tsunami (MOST) model, NOAA Tech. Memo. ERL PMEL!112 (PB98!122773), 11 pp., Pac. Mar. Environ. Lab., NOAA, Seattle, Wash.

Wikipedia contributors, "El Salvador," Wikipedia, The Free Encyclopedia, http://en.wikipedia.org/w/index.php?title=El_Salvador&oldid=523734824 (accessed November 21, 2012).