ABSTRACT

Keywords: Tsunami, El Salvador, seaquakes, run-up, earthquakes, seismic hazard, tsunami catalogue, probabilistic assessment, warning systems.

El Salvador can be catalogued as a potential tsunamigenic country. Being in the Pacific, where the majority of tsunamis have been recorded, the country can be considered likely to be hit by a tsunami. This thesis illustrates the tsunami hazard potential in El Salvador. A theoretical frame containing general concepts and definitions, geological settings of El Salvador and previous studies related to tsunamis in Central America and El Salvador is presented. Historical tsunami information contained in the Central America tsunami catalogue and more specifically in the Salvadorian tsunami catalogue was gathered and levels of accuracy and reliability of both catalogues were established. The information contained in the Salvadorian tsunami catalogue was used to perform a probabilistic tsunami hazard assessment of El Salvador after estimating the completeness of the catalogue. Based on historical information, two locations at the Salvadorian coast (Acajutla and La Union) were identified as tsunami hazard scenarios. Maximum run-up values for return periods of 250 and 475 years were estimated at each location. Logic tree analysis was performed to associate some level of likelihood of those estimated run-ups being correct. Estimated run-up values at Acajutla are 9.62 and 12.08 meters for return periods of 250 and 475 years respectively whereas at la Union run-up values are expected to reach 3.70 and 4.68 meters for the same return periods. According to the results obtained from the analyses, destructive tsunamis are likely to hit El Salvador, therefore a tsunami warning system, evacuation plan and tsunami educational programs are needed in order to avoid high death tolls if a tsunami occurs. Tsunami warning systems that are currently operating around the world are described. Some conclusions regarding to tsunamicity of the country obtained from the analyses and recommendations for future research are made.

ACKNOWLEDGEMENTS

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TSUNAMI HAZARD ASSESSMENT OF EL SALVADOR

INDEX

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. MOTIVATION FOR THE STUDY

Located at the Pacific coast of Central America, El Salvador is the smallest and most densely populated country of the region. Its area covers 21,393 km^2 and its population reaches 5,580,000 inhabitants. The country is located in a high seismicity area where earthquakes, landslides and mudslides are considered major natural hazards.

Since the destructive 1992 Nicaraguan tsunami the Central American countries started to increase their awareness of the occurrence of such events in the region. Some tsunami studies performed after 1992 revealed that the Pacific coast of Central America is prone to be hit by tsunami waves, nevertheless, no tsunami warning system has been implemented in the region. The need of setting tsunami early warning systems to save lives in case of tsunami has been recently reaffirmed by the disastrous 26 December 2004 Asian event.

This thesis is aimed to illustrate the tsunami hazard potential of El Salvador by reviewing previous studies in tsunamis, gathering tsunami catalogues previously made for Central America and El Salvador, investigating levels of reliability and accuracy of the data compiled in the catalogues, establishing the completeness of the Salvadorian catalogue, performing a probabilistic tsunami hazard assessment that allows estimating vertical run-up values at different points located at the Salvadorian coast and setting the need of starting a tsunami warning system.

1.2. RESEARCH OBJECTIVES

The main research objectives that have been fulfilled in this study are:

- Identify and review previous tsunami-related studies of El Salvador.
- Describe the geological setting of El Salvador and identify potential tsunami triggering mechanisms.
- Obtain historical tsunami data registered or recorded in El Salvador, namely retrieve the Salvadorian Tsunami Catalogue.
- Investigate the levels of reliability and accuracy of the Salvadorian Tsunami Catalogue and establish the completeness of the Salvadorian Tsunami Catalogue.
- Perform a probabilistic hazard assessment that allows estimating vertical run-up values at different points located at the Salvadorian coast.

- Describe different types of tsunami warning system and illustrate the warning systems that are already operating in other parts of the world.

1.3. METHODOLOGY

General concepts and definitions on tsunami terminology were recalled by reviewing books, glossaries and articles on tsunamis. In some cases, written communication with some of the authors of reviewed articles was reported to enlarge the body of knowledge on this subject.

Historical information was obtained from literature review and written communication with the “Servicio Nacional de Estudios Territoriales” (SNET) of El Salvador. Levels of reliability and accuracy of the Central American and the Salvadorian tsunami catalogues were established based on written documents and also on written communication with the authors. The visual cumulative method was used to estimate completeness of the Salvadorian tsunami catalogue.

Historical data provided by the Salvadorian tsunami catalogue was used to perform the probabilistic analyses to establish the tsunami hazard potential in the country. A computer code was written to perform the regressions required by the probabilistic analysis.

Information regarding to tsunami warning systems was obtained from literature review. Some conclusions were written based on the results obtained from the analysis performed. Some important aspects for future research were recommended in order to have a better approach of tsunami hazard in El Salvador.

1.4. DISSERTATION OUTLINE

This thesis can be divided in six main chapters. The first chapter contains the introduction, research objectives, methodology and dissertation outline of the study.

The second chapter of the document contains a literature review on the subject, where the reader is introduced to tsunami terminology and causes of tsunamis in general. The geological setting of El Salvador is presented in chapter 3, where tectonic environment, bathymetry and relevant tsunamigenic sources of the country are described.

Chapter 4 lists previous studies on tsunamis performed for El Salvador and Central America as well as location of affected areas. The Salvadorian Tsunami Catalogue, its accuracy, reliability and completeness are presented in Chapter 5. The probabilistic tsunami hazard assessment in El Salvador, input data, results and logic tree analysis are presented in chapter 6.

Tsunami Warning system schemes that have been already implemented in countries affected by these events around the world, and proposals of tsunami warning systems in Central America are presented in chapter 7.

Conclusions from the probabilistic tsunami hazard assessment performed in this document and recommendations for future research are presented in chapter 8.

2. LITERATURE REVIEW

2.1. GENERAL CONCEPTS AND DEFINITIONS

Tsunamis[1] are water waves due to displacement of the seafloor (Fernández, M., et al, [2004]). These displacements are usually triggered by earthquakes, submarine landslides, volcanic eruptions or meteorite impacts. Although splashing of solid material (e.g. rock, ice) and meteorological events can also generate tsunami-like waves, these events are not tsunamis. Tsunami waves can be generated in oceans, seas, bays, fiords, lakes or reservoirs (Bryant, E. [2001]).

In general terms, tsunamis are train waves that are sinusoidal shaped in deep water but become peak shaped in shallower water. The amplitude of each wave increase when it approaches the shoreline; for example, in the open sea a tsunami wave reaches about 0.3 to 0.6 meters (UNESCO, [1991]), whereas near the coastline can reach several meters depending on the coastline configuration and the shape of the ocean floor. In deep waters tsunami waves can reach velocities higher than 700 km/h and their wavelength values can be higher than 750 km (González, F. [1999]). The velocity of the waves decreases as the tsunami approaches shallow waters taking values as low as 36km/h near shore (Bryant, E., [2001]).

The coastal regions hit by tsunamis are usually flooded and the size of the affected area depends on the amplitude (or size) of the waves near shore, coastal configuration and use of coastal land. The tsunami parameters, *run-up* and *inland penetration*, describe the wave size at furthermost dry lands and determine the inundation area. The tsunami *run-up* is the difference between the elevation of maximum water penetration and the sea level when the tsunami occurs (see Fig. 2.1), and the *inland penetration* is the distance from the shoreline to the furthermost flooded place (see Fig. 2.1). An additional parameter is the so-called *arrival time*, which is the time that the waves take to travel from the source to the coast and inland (ITIC/UNESCO, [http://www.shoa.cl/oceano/itic/frontpage.html]).

When a tsunami strikes a coastline, *run-up* and *inland penetration* differ from point to point along the coast. *Run-up distributions maps* show the values observed or measured at different places affected, one of these maps is shown in Fig. 2.2.

Another concept related to tsunamis is *travel time,* which is the "time required for the first tsunami wave to propagate from its source to a given point on a coastline" (ITIC/UNESCO, [http://www.shoa.cl/oceano/itic/frontpage.html]). Travel time is shown in maps containing *isochrones,* that are lines of equal tsunami travel time starting from the source to distant points, as shown in Fig. 2.3.

[1] From the Japanese (tsun) harbour (ami) wave.

Tsunami *run-up* is measured using *tidal gauges* at different points of the coast, whereas inland penetration is measured through field survey some time after the tsunami occurred by the observation of water traces in buildings, or vegetation destroyed by salty water.

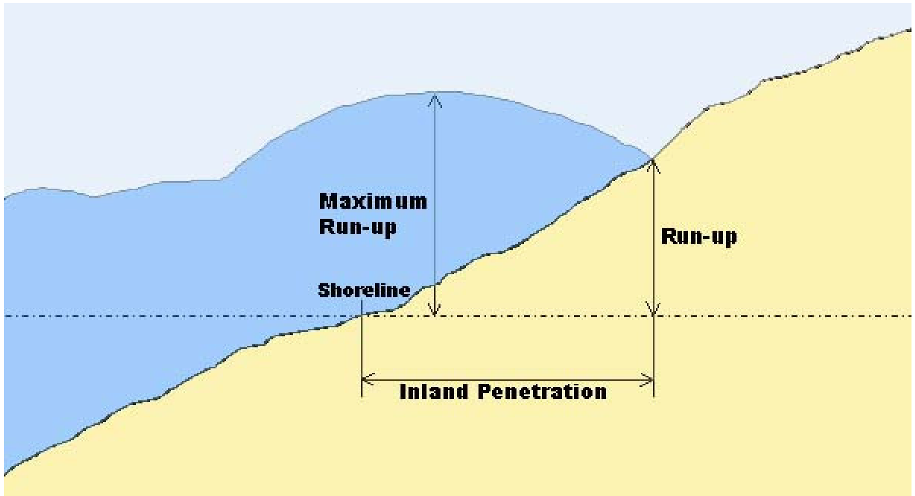

Figure 2.1: Vertical and Horizontal Tsunami Run-up.

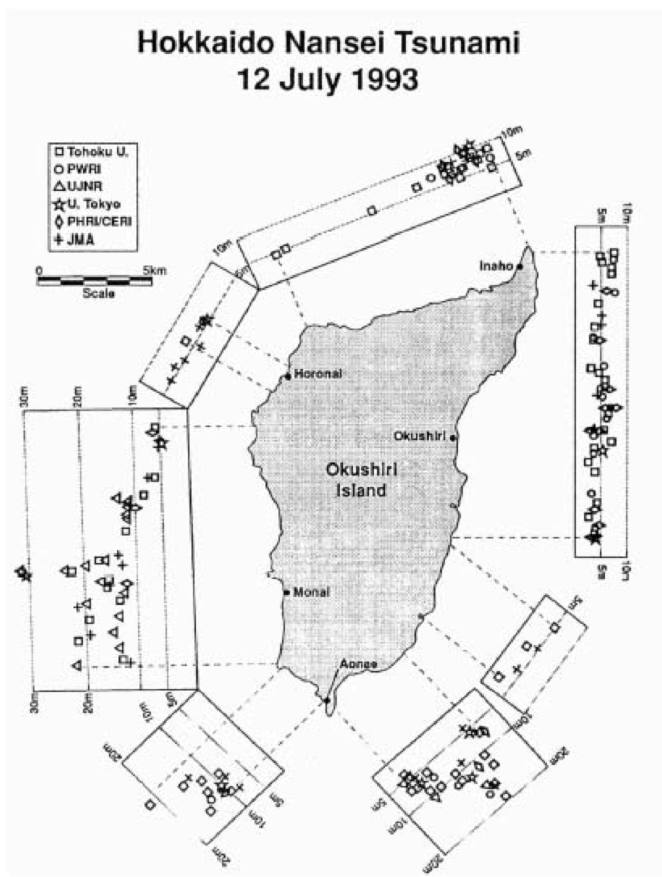

Figure 2.2: Vertical run-up distribution map of the 12 July 1993 Hokkaido Nansei (Japan) Tsunami.

[http://www.shoa.cl/oceano/itic/frontpage.html]

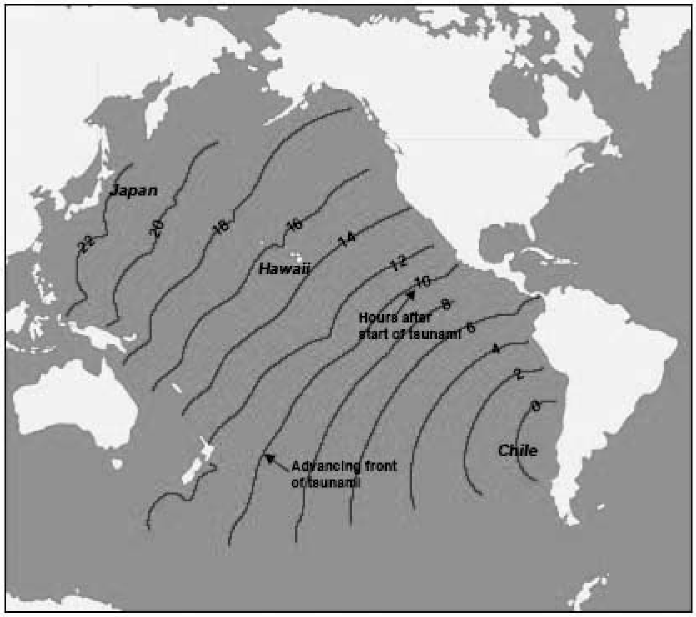

Figure 2.3: Travel time tsunami maps.

[http://www.shoa.cl/oceano/itic/frontpage.html]

Tsunami run-up values depend basically on the coastal topography and the volume of water excited by the seafloor displacement. The inland penetration is also determined by the former factors plus the coastal surface roughness (defined as *Manning coefficient*[2]) and the use of the land (in other words the physical barriers that the tsunami waves would find, as buildings, trees, rocks, cliffs, etc). Tsunami run-up values and arrival time can vary drastically at different points of the coast basically due to changes in coastal configuration, topography and seafloor shape. Depending on the shore geometry the following phenomena could amplify the tsunami impact: diffraction, resonance, waves perpendicular to the shoreline (edge waves) and trapping of the incident wave by refraction or by a reflected wave (Bryant, E. [2001]).

Considering their *run-up* values (height) and the damage that they produce, tsunamis can be classified under the Inamura-Iida magnitude Scale, shown in table 2.1, this scale is commonly used to describe tsunami magnitudes worldwide. Tsunami magnitude (m) under the Inamura-Iida scale takes values between 4 and –1, and it follows the relation $m = \log_2 H$, where H is the maximum run up value registered in a coastline near the tsunami generating area (ITIC/UNESCO, [http://www.shoa.cl/oceano/itic/frontpage.html]).

Tsunamis can also be classified as local, regional and distant regarding to their propagation distance from the place where they were generated. Local tsunami waves can propagate up to 100 km, whereas regional tsunami waves travel up to 700 km and distant tsunami waves more than 700km (Fernández, M. and Rojas, W., [2000]). Locally triggered tsunamis generally have shorter arrival times than regional and distant tsunamis and that makes them more dangerous, specially when people cannot be warned on time; nowadays some countries are able to issue tsunami warnings within few minutes from their generation (Fernández, M., et al., [2004]).

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[2] The Manning coefficient or roughness can be computed as $n = \frac{1}{v} * R^{\frac{2}{3}} S_f^{\frac{1}{2}}$, where n is the manning coefficient, v is the average flow velocity, R is the hydraulic radius and S_f is the friction slope.

Table 2.1 Tsunami Magnitude Scale Inamura-Iida.

(Molina, [1997])

m	Hmax	Hmin	Damage
4	30	30	Considerable damage along more than 500 km of coast line
3	20	10	Considerable damage along more than 400 km of coast line
2	6	4	Damage and lives lost in certanin landward areas
1	2	2	Coastal and ship damage
0	1	1	Very small damage
-1	0.5	0.5	None

Tsunamis can be extremely devastating[3] events and avoiding them is so far impossible, unfortunately. The solution to at least decrease the impact of these events is first of all assessing the tsunami hazard at the coasts that have experienced them in the past, secondly setting an adequate warning system and evacuation plan according to the regional needs found, and last but not least, it is important that the inhabitants of regions at risk know what to do in case a tsunami occurs.

Addressing a tsunami hazard assessment means first establishing if the region under study is likely to be hit by tsunamis, second, computing the estimated tsunami parameters that could be registered in the region and third, drawing zoning maps that help to identify different hazard levels in the region. There are two kinds of tsunami hazard assessment approaches: the probabilistic approach and the deterministic approach. The former finds the tsunami probability occurrence law that governs the region whereas the latter determines, using numerical modelling, the tsunami parameters that a hypothetical event would produce in a scenario. No matter what assessment approach is taken, it is crucial to define the potential tsunami *triggering mechanisms*, namely the potential causes of tsunamis in the region (these causes will be explained in section 2.2). Tsunami hazard assessment of El Salvador is described in Chapter 6.

Once the tsunami hazard assessment is done, and the tsunami triggering mechanism have been determined, it is necessary to set up an early warning system that monitors permanently the potential occurrence of tsunamis and that is able to issue early alarms to evacuate people at risky areas. These people should be aware of the evacuation plan. Chapter 7 will be devoted to tsunami warning systems.

2.2. CAUSES OF TSUNAMIS

Several tsunamis have been recorded throughout the human history, these events are called *historical tsunamis*. There are tsunamis that have not been recorded directly, but geological evidence of their occurrence have been found, these events are called *paleotsunamis*. Compilations of paleotsunami and historical tsunami data are called *tsunami catalogues*. These compilations are generally made for specific regions and they usually contain information regarding the places affected by tsunamis, run-up values, dates, tsunami triggering mechanisms and sometimes descriptions of the damage caused by these events. The tsunami triggering mechanisms of a region can be generally found by revising tsunami catalogues.

Considering the tsunamis registered worldwide, the most tsunami-affected region has been the Pacific Ocean where more than 25 % of tsunamis have been recorded, closely followed by the East Indies at 20.3 % and the Japanese and Russian coasts at 18.6%. Taking the tsunamis recorded in the Pacific Ocean; earthquakes, volcanic eruptions and submarine landslides can be cited as the main

[3] The 26 December 2004Asian tsunami can be cited as an example of a devasting tsunami.

causes of tsunami. Around 8% of these tsunamis have not been associated to any triggered mechanism (Bryant, E. [2001]). See in this regard information illustrated in table 2.2.

Table 2.2: Causes of Tsunami in the Pacific Ocean Region over the last 2,000 years

(Bryant, E. [2001])

Cause	Number of events	%	Number of deaths	%
Landslides	65	4.6	14,661	3.17
Earthquakes	1171	82.3	390,929	84.51
Volcanic	65	4.6	51,643	11.16
Unknown	121	8.5	5,364	1.16
	1422	100	462,597	100

According to table 2.2, in the Pacific Ocean earthquakes have been the most common cause of tsunamis at 82.3%, whereas volcanic eruptions and landslides have each triggered 4.6 %. The same pattern is observed when it comes to number of deaths[4], tsunamis triggered by earthquakes have caused around 84.5% of the total deaths while tsunamis due to volcanic eruptions and landslides have caused around 11% and 3% of the deaths, respectively.

2.2.1 Tsunamigenic earthquakes.

Studying tsunami-generating processes is important for implementing early warning systems that help to mitigate the impact that tsunamis could cause when striking inhabited coasts. Earthquakes are the most common tsunami-triggering mechanism. T*sunamigenic earthquakes* and *tsunami earthquakes* have caused around 82% of the total tsunamis registered in the Pacific Ocean (see table 2.2). The characteristic of both tsunami triggering mechanism will be described in the following.

Tsunamigenic earthquakes are all those earthquakes that generate tsunamis (Satake, et al, [1992]). These seismic events are usually located offshore or inland at small distances from the coast. Surface wave magnitudes (M_S) of tsunamigenic earthquakes generally exceed 6.5, their focal depth is commonly less than 100 km and their seismic mechanisms can be strike-slip, normal and thrust faulting (Bryant, E. [2001]), see [Fig. 2.4].

As mentioned before, earthquakes are the most common cause of tsunamis. Examples of tsunamigenic earthquakes are the 22 May 1960 Chilean event (see section 2.3.1 for more details), the 9 October 1995 Jalisco-Colima earthquake and the 21 February 1996 Peruvian earthquake.

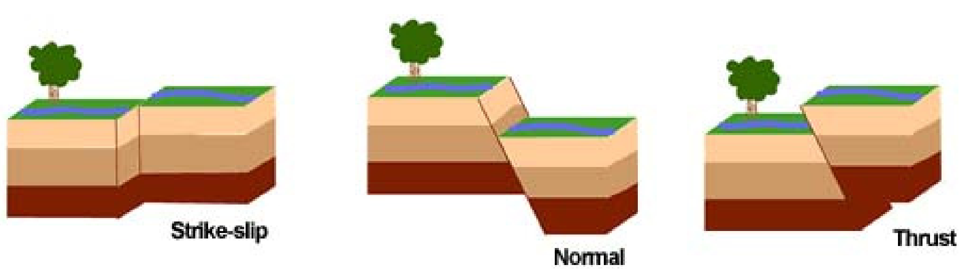

Figure 2.4: Main Fault Types.

(USGS [http://earthquake.usgs.gov/image_glossary/fault.html])

[4] This information is based on data gathered before the 26 December 2004 Asian Tsunami.

Tsunami earthquakes are offshore earthquakes that cause slow rupture along faults lines (Bryant, E. [2001]) and generate a large tsunami relative to its magnitude (ITC/UNESCO [http://www.shoa.cl/oceano/itic/frontpage.html]). Those earthquakes have very shallow foci, fault dislocations that reach several meters and fault surfaces smaller than for normal earthquakes. Tsunami earthquakes are slow earthquakes and their slippages occur more slowly than for normal earthquakes (ITC/UNESCO [http://www.shoa.cl/oceano/itic/frontpage.html]).

The main characteristics of the *tsunami earthquakes* are that first their surface wave magnitude M_s and their moment magnitude M_w differ considerably (about half a unit or more), being the latter generally higher than 7, second tsunami earthquakes frequencies are low and their periods are usually greater than 100 seconds, and third their seismic force describes a smooth curve along the time in contrast with the fast rupture earthquakes whose force peaks several times during while the earthquake occurs. In some cases tsunami earthquakes are barely felt by the coastal inhabitants (Bryant, E., [2001]).

The 2 September 1992 Nicaraguan tsunami can be cited as an example of tsunami earthquake event. The earthquake was barely felt by coastal inhabitants although the surface wave magnitude was very high. Long waves reached coastal land (shaking the ground gently) whereas short waves dissipated quickly from the epicentre and did not reach the coast. Standard seismometers did not record the long waves, that leads to the conclusion that the waves had very long periods since that kind of equipment are able to record periods less than 20 seconds. The earthquake triggered waves whose run up reached between 2 and 10 meters (see section 2.3.1) (Bryant, E. [2001], Satake et al, [1993] and Gonzalez, F. [1999]).

There are three aspects of the earthquakes that are related to tsunamis: the seismic moment, the earthquake mechanism and the earthquake depth. The seismic moment is computed as the product of the rigidity of the source's soil, the fault area and the average fault slip and it is an indicator of the tsunami size. Being all the other conditions the same, it can be said that the bigger the seismic moment, the bigger the tsunami. The earthquake mechanism indicates the orientation of the earthquake and the direction of the fault slip. Events with large vertical slip are usually more effective triggering tsunamis than those with large horizontal slip. Finally, the earthquake's depth is also an important factor to consider in the generation of tsunamis. The shallower the event, the greater are the chances to trigger a big tsunami since a larger slip is likely to been produced (Bryant, E., [2001]).

For warning and monitoring purposes, it is useful to link earthquake magnitudes to tsunami registered vertical run-ups in order to find the minimum earthquake magnitude value that could trigger tsunamis. This value is usually found by establishing regional relations that relate vertical run-ups and moment magnitude M_w of historical tsunamis (Bryant, E., [2001]).

2.2.2 Landslides.

Landslides are displacement of soil in coherent blocks that generally occur in steep slopes (see Fig. 2.5), these events may be due to earthquakes, soil instability or gravity effects whenever water saturation of the soil occurs during raining seasons or flooding. If these events occur at the seafloor they are called submarine landslides.

Submarine landslides occur at slopes less steep than 1° at the seafloor (Ward, S. and Day S., [2002]). They are mainly caused by earthquakes, but some other causes can be listed: first the loading-unloading processes (over steep slopes) due to big tidal waves generated by meteorological phenomena. Second the failure of non-consolidated or weak soil layers that lie beneath heavier layers of material and third the failure of soil due to the accumulation of gasses in voids when decomposition of organic sediments occurs (Bryant, E., [2001], Ward N. and Day S., [2002]).

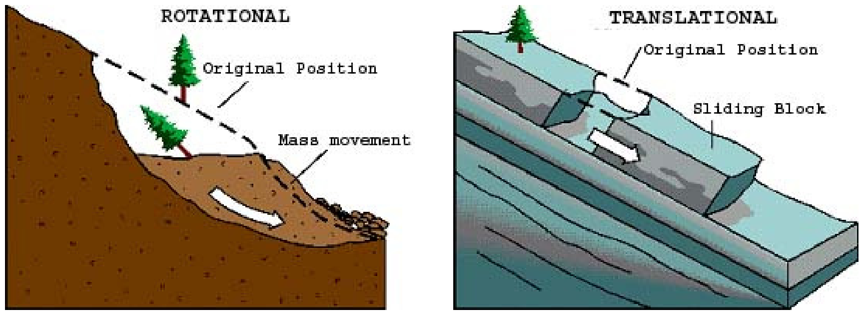

Figure 2.5: Rotational and translational landslides.

[www.milarium.com]

The following three processes related to landslides are able to generate tsunami waves: first the sliding of soil blocks on steep slopes, second the disintegration of soil blocks when that generates debris flows (see Fig. 2.6) and third the generation of turbidity currents that occur when water is involved in a debris flow. If the volume of material involved in those three processes is large enough, a tsunami is originated. The size of tsunamis generated by landslides depends on the volume of material involved, the depth at which the landslides occurs and the sliding velocity of the material (Bryant, E., [2001]).

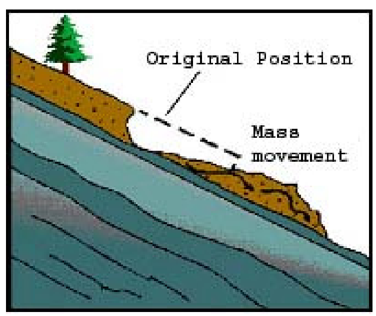

Figure 2.6: Terrestrial Debris flow.

[www.millanium.com]

Landslides are considered a minor cause of tsunamis. This must be due to the fact that earthquakes cause many of the submarine landslides that generate tsunamis, and then those earthquakes are considered the triggering mechanism. Additionally, detecting submarine landslides is difficult when there is not previous knowledge of the seafloor topography (bathymetry), since displacements of material cannot be recognised (Bryant, E., [2001]).

Tsunamis caused purely by landslides have not been recorded directly, however, there are some historical events related to landslides for example the 9 July 1958 Lituya Bay (Alaska) event and the Grand Banks (Burin Peninsula, Canada) tsunami in 1929 (see section 2.3.2) (Bryant, E. [2001]).

2.2.3 Volcanic eruptions.

Volcanic eruptions can cause tsunamis depending on the location of the volcano with respect to the ocean. Submarine volcanoes are more likely to cause tsunamis than inland volcanoes located in the vicinity of the ocean. The processes related to volcanic eruptions that could trigger tsunamis are described in the following.

Submarine volcanic eruptions can cause big tsunamis if the volcano lies up to 500 meters below the sea level. Eruptions of deeper volcanoes cause small tsunami waves that generally travel no more than 150 kilometres (Bryant, E., [2001]), however, the formation of a deep underwater volcanic caldera could trigger a large tsunami depending on the size of the caldera (Fernández, M. [written communication]).

When submarine volcanic eruptions occur, tsunamis can be triggered if underwater explosions are generated when water penetrates into the volcano magma chamber becoming vapour. Tsunamis could also occur whenever explosions are big enough to generate a caldera, which is a large approximately circular, steep-walled basin of several kilometres in diameter (Skinner, B. and Porter, S. [1992]). The depression is then filled with water and that propitiates the generation of waves due to the water displaced (Bryant, E., [2001])..

Tsunamis generated by surface volcanic eruptions are due to explosions and debris avalanches or lahars[5]. Inland volcanic explosions can generate tsunamis if they are close enough to deposit large amounts of solid material in the ocean, for example if the volcano is located at about 20km from the coast (Fernández, M. [written communication]). If that is the case, pyroclastic flows can hit the ocean transferring energy or displacing water depending on the ash density. If the ash density is low, energy is transferred as the ash float on the ocean generating a small wave. On the contrary, if the density is high, the ash submerges displacing water that can trigger a tsunami depending on the volume of material involved (Bryant, E., [2001]). Debris flows or lahars produced by inland volcanic eruptions can trigger tsunamis when large amount of transported material reach the ocean. These avalanches can travel about 100km from the volcano and their speeds can reach 200km/h (Tarbuck, E. and Lutgens F., [2003]).

Through history, explosive eruptions in or near the ocean and debris avalanches or pyroclastic flows have been found to be the most common causes of volcanic tsunamis (Beget, J., [2000]). The most famous tsunami caused by a volcanic eruption is the Krakatau (Indonesia) event in 1883, which generated 3 main explosions that triggered a local tsunami and 2 distant events (Bryant, E. [2001]). More details about the Krakatau event are presented in Section 2.3.3. Another tsunami triggered by volcanic eruption is the 1 February 1954 event occurred in Stromboli, Italy (NOAA tsunami catalogue http://www.ngdc.noaa.gov/seg/hazard/tsevsrch_idb.shtml).

2.2.4 Meteorite impact.

Any celestial body with a large mass that enters the Earth and that is not disintegrated by atmospheric friction could cause a tsunami. The impact will directly displace a mass of water and possibly generate a tsunami if the impact affects the ocean floor. If that is the case, a cavity is formed on the seafloor and it is filled with water and tsunami waves are triggered due to the water displaced. The tsunami waves size depends on the amount of water displaced and the diameter of the crater formed[6], which is always bigger than the celestial body diameter (Bryant, E., [2001]). Previous studies show that the smaller the crater formed the shorter the water wavelength and the higher the expected wave dispersion with distance (Hills, J. and Goda, P. [2001]).

Even though the probability of meteorite collision with the earth is low, the effects of such event would be destructive at different scales depending on the diameter of the meteorite. For example, if

[5] Lahars are debris flows and/or mudflows produced by loose soil and rock flowing down the sides of a volcano.

[6] 60% of the known objects that have impacted the Earth are "earth-obit-crossing" asteroids whereas 20% were long period commets and 20% period commets. All of them have formed craters greater than 10km. (Solem, J. [1999])

an up to 1-kilometre in diameter collides with the Earth severe local damage is expected whereas if the diameter is greater than 1 kilometre the collision will have a global devastating effect (Solem, J., [1999]).

There is no recorded historical information about tsunamis generated by meteorite impact. However, scientific evidence suggests that there have been some tsunamis caused by this type of events. The Cretaceous Tertiary Extinction event due to the landing of a meteorite in the Mexican Gulf is an example of these events, see Section 2.3.4 for more details(Bryant, E., [2001]).

Since 1990, the possible damage that tsunamis due to meteorite impact could have caused has been determined using numerical simulations. Some researches have discrepancies when estimating some of the initial conditions needed to implement numerical simulation such as initial size of the wave and rate of run-up dissipation with distance (Paine, M., [1999]).

2.2.5 Meteorological events.

Meteorological events such as typhoons, pressure fronts, atmospheric pressure jumps or atmospheric gravity waves could generate long period tsunami-like waves. These waves are called “meteorological tsunamis”, “atmospheric tsunamis” or “air-coupled tsunamis”. The tsunami-like waves are generated when an atmospheric pressure front moves rapidly over shallow waters at about the same speed as the waves, allowing them to couple. They are recurrent phenomena and occur generally in bays, lakes and harbours (Bryant, E., [2001] and ITC/UNESCO [http://www.shoa.cl/oceano/itic/frontpage.html]).

In this regard, there are a couple of phenomena that are somehow similar to tsunamis: *freak waves* and *storm surges*. The former are generally one-wave event caused by water displaced by ships or by isolated landslides that are not linked to any earthquake. The latter are also one-wave events caused by tropical cyclones. Even if their inland penetration and height are similar to tsunami run-up values, freak waves and storm surges cannot be called tsunamis, since both of these events involve transport of only shallow waters whereas tsunamis are train waves that move the entire column of water. Sometimes these meteorological events are confused with tsunamis with no triggering mechanism associated (Bryant, E., [2001]).

2.3. HISTORICAL CASES

Historical tsunami information started to be recorded at different times all over the world. In China, for example, tsunami information dates back approximately 4000 years, whereas in the Mediterranean Sea and Japan there is a record of information from about 2000 and 1300 years ago, respectively. The Americas started recording tsunami data around 400 years ago, and countries like New Zealand and Australia have compiled in the 1990’s tsunami information corresponding to 150 years ago (Bryant, E., [2001]).

In areas where no historical records are available, geological deposits can be used to estimate the magnitude and frequency of occurrence of tsunamis (events registered under this procedure are called *paleotsunamis*). Morphological and sedimentological characteristics of geological deposits are used to identify areas affected by tsunamis and probable time of occurrence (Not, J., [2000]).

Some of the recorded historical tsunamis due to earthquakes, landslides and volcanic eruptions will be described in the next section. Tsunamis due to meteorite impact have not been recorded in the human history. However, an example of these type of events will be described as there is ample geological evidence that demonstrates that such event has occurred in the past.

2.3.1 Historical tsunamis triggered by earthquakes

As mentioned before, earthquakes that trigger tsunamis can be classified as *tsunamigenic earthquakes* and *tsunami earthquakes*: example of the former is the 22 May 1960 Chilean tsunami whereas the 2 September 1992 Nicaraguan tsunami represents an example of the latter. The former is a tsunamigenic earthquake and the latter a tsunami earthquake. These two events were chosen due to the fact that both of them were recorded inside the region of study.

The 22 May 1960 Chilean tsunami was caused by an M_s 8.5, M_w 9.5 earthquake located at 39.5º S 74.5º W and a 33 km depth focus within the eastern edge of the Nazca Plate. The earthquake was the last of about 50 events that went along 2 days in the region and affected about 1,000 km of a fault. Near the source, uplift values were found to be as great as 1 m, and 1.6 m of subsidence was observed along 300 km. Several tsunami waves were generated, the first wave struck more that 500 m along the Chilean coast within 10 to 15 minutes after the earthquake, while the second and third took about 50 minutes and 1 hour for arriving, respectively. The first wave reached about 4 to 5 meters *run-up*, the second and third waves reached about 8 and 11 meters respectively. The tsunami propagated northwards and it affected around 630 sites around the Pacific, see Fig. 2.7 (Bryant, E., [2001] and Earth And Space Science, University Of Washington http://www.geophys.washington.edu/tsunami/general/historic/chilean60.html).

On 2 September 1992, an M_s 7.0, M_w 7.7 earthquake occurred 100 km offshore Nicaragua at 45 km depth within the Cocos-Caribbean Plate *subduction* zone in the Pacific Coast. The event lasted about 100 seconds; its rupture length was estimated as 100 km wide by 200 km long and the velocity of rupture of about 1 to 1.5 km/s. The earthquake was barely felt by the coastal inhabitants, but it generated a very destructive tsunami that hit the coast between 40 and 70 minutes later. *Run-up* heights measured at different points at Nicaraguan Coast varied between 2 and 6 meters. The maximum *run-ups* recorded were about 10 meters. The tsunami struck mainly the Nicaraguan Coast, other Central American countries recorded small tsunami waves. After this event 170 fatalities and about 13,000 homeless were reported. The direction of propagation was westwards and 10 cm-height waves were recorded in Japan and Hawaii. Figure 2.8 shows the run up distribution along the Nicaraguan coast, a 200 meter depth contour line curve is also shown (Bryant, E., [2001], Satake et al., [1993], Gonzalez, F., [1999]).

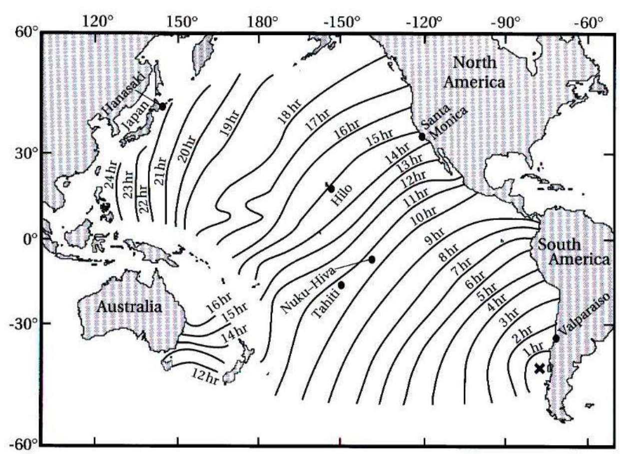

Figure 2.7: Propagation of the 1960 Chilean Tsunami.

(Bryant, E., [2000])

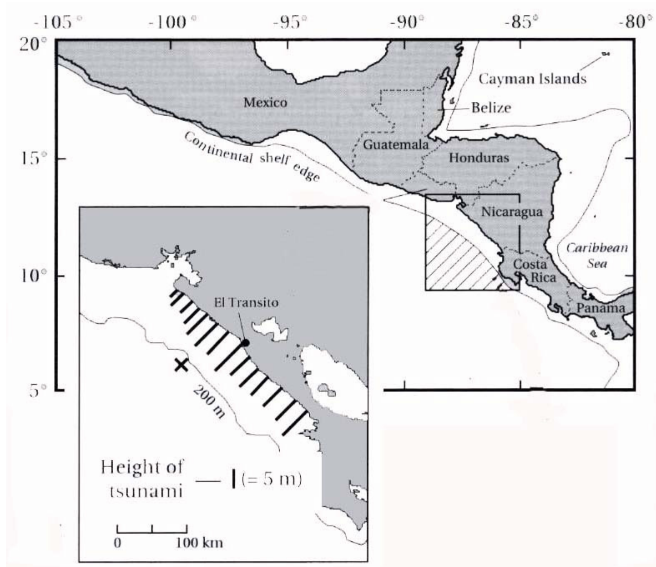

Figure 2.8: Run-up heights of the 1992 Nicaraguan Tsunami.

(Bryant, E., [2000])

Sometimes, earthquakes can also generate terrestrial or submarine landslides that triggered tsunamis depending on factors such as the volume of material involved and the location of the landslides. Historical tsunami due to landslides will be described in Section 2.3.2.

2.3.2 Historical tsunamis triggered by landslides

Landslides due to earthquakes, accumulation of voids and gasses or failure of weak soils that support heavier layers of geomaterials can trigger tsunamis. Along the history, terrestrial and submarine landslides induced by earthquakes have been found to be the cause of some tsunamis, for example the 9 July 1958 Lituya Bay in Alaska and the 18 November 1929 Grand Banks tsunami. Some details of these two events will be described in the sequel. Although tsunamis generated by purely geological phenomena have not been directly recorded, evidence of their occurrence have been found, for example the tsunami related to the Storegga slides, near Norway (Bryant, E., [2001]), Ward, S. and Day S., [2002]). Another tsunami that has been associated to landslides is the 3 November 1994 Skagway (Alaska) event (Campbell, B. and Nottingham, D., [1999]).

Tectonic movement, displacement of a glacial front, a big terrestrial rockfall and the sudden drainage of a subglacial lake have been proposed as the cause of the giant wave generated in the Lituya (Alaska) tsunami on 9 July 1958. Some authors believe that none of these mechanisms could have triggered such a big wave by itself, however. The most likely mechanism that could have generated this event is a major terrestrial landslide that was induced by an earthquake whose surface wave magnitude (M_s) was estimated to be about 7.9 to 8.3. The vertical and horizontal dislocation related to the earthquake was 1.1 and 6.3 meters respectively. The landslide started about a minute after the seismic event, and it involved about 30.5×10^6 m^3 of consolidated rock that fell between 600 to 900 meters down slope. The impact splashed water at 524 m above the sea level. A 30 m *solitary wave* was induced by water displacement and travelled along the bay. See Fig. 2.9 (Bryant, E., [2001], and Tsunami, earthquakes, hurricanes, volcanic eruptions and other Natural and Man-made hazards and disasters [http://www.drgeorgepc.com/Tsunami1958LituyaB.html]).

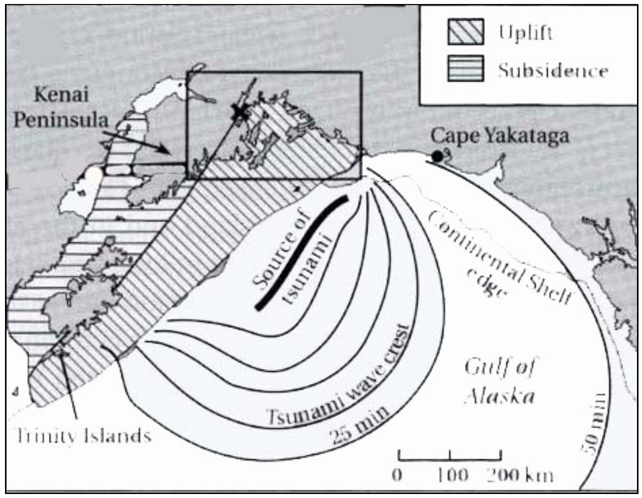

Figure 2.9: Propagation of the 1958 Alaskan Tsunami.

(Bryant, E., [2000])

The 18 November Grand Banks (Burin Peninsula, Canada) tsunami is an example of tsunami triggered by submarine landslide, even if the latter event was due to an offshore earthquake. The landslide consisted of rotational slumps. Some of the slumps were around 2 to 5 m thick, some as large as 30 m thick. The tsunami was triggered during the translation when those slumps became debris and were mixed with seawater generating turbidity currents that travelled around 110 km down slope. A 3-meter wave was recorded at the Burin Peninsula. See Fig. 2.10 (Bryant, E., [2001]).

As mentioned before, tsunamis generated by landslides induced by purely geological processes have not been directly observed. Indirect evidence of their occurrence has been found, however. For example, studies of soil profiles in Scotland have detected layers of sand of different sizes, some times mixed with silt and containing shell, plant and mollusc fragments. It is said that the layers of soil were transported by tsunami waves that were triggered by two slides occurred in Storegga around 6000 to 8000 years ago, see Fig. 2.11. Both slides are supposed to have displaced around 1700 km^3 of soil triggering 8 to 12 meter tsunami *run-ups* at Scotland and Norway (Bryant, E., [2001] and Ward S. and Day, S., [2002]).

Run-up values as high as 2.7 metres, one fatality and damage to local harbour structures were reported when the 3 November 1994 Skagway (Alaska) tsunami occurred. This event has been found to be related to an underwater landslide occurred in the delta of the Skagway River. At first, the landslide was associated to construction activity in the harbour that was held at that moment, but studies revealed that the factors that contributed to the landslide are the delta overloading caused by sediment (transported by the stream) and steep slopes on the walls of the river. The volume of soil involved in the slide has been estimated to be approximately 15,300,00 m^3. Topographic maps of the area drawn after the tsunami were compared to previous maps in order to describe the landslide. Figure 2.12 shows the results obtained. (Campbell, B. and Nottingham, D., [1999])

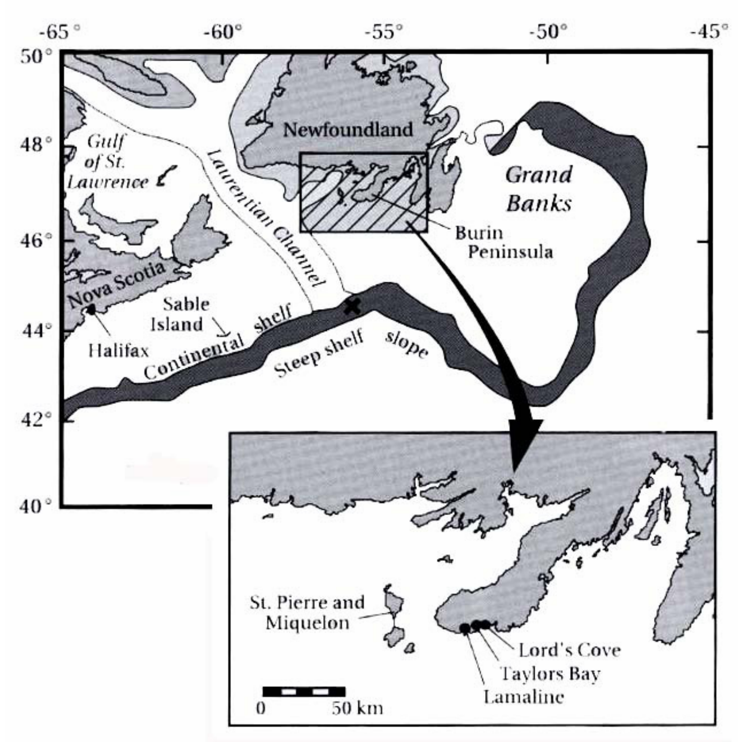

Figure 2.10: 18 November 1929 Burin Peninsula (Canada) Tsunami.

(Bryant, E., [2000])

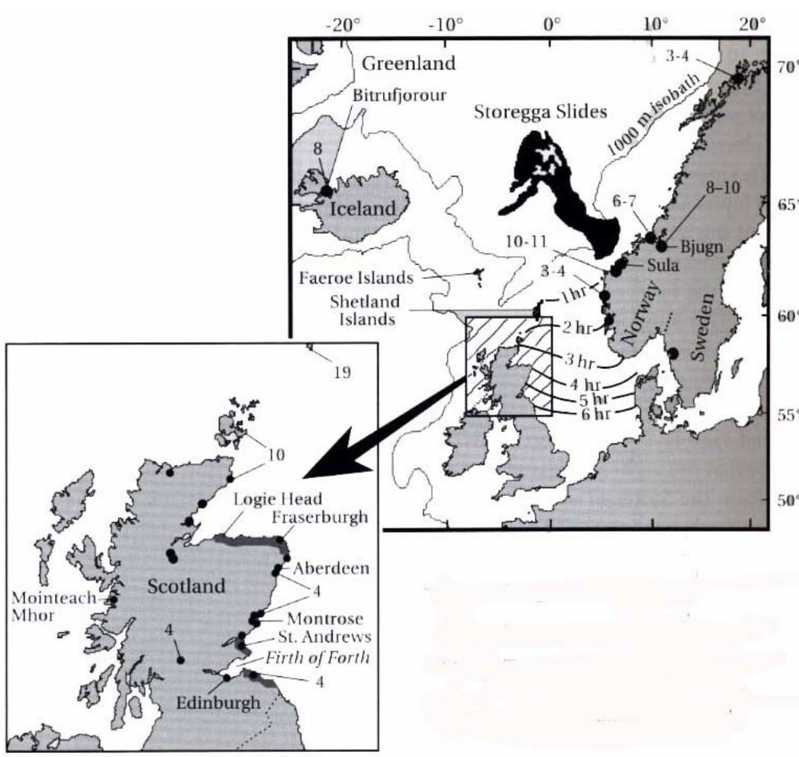

Figure 2.11: Tsunami propagation due to the Storegga Slides (Norwegian Sea) about 6000-8000 years ago.

(Bryant, E., [2000])

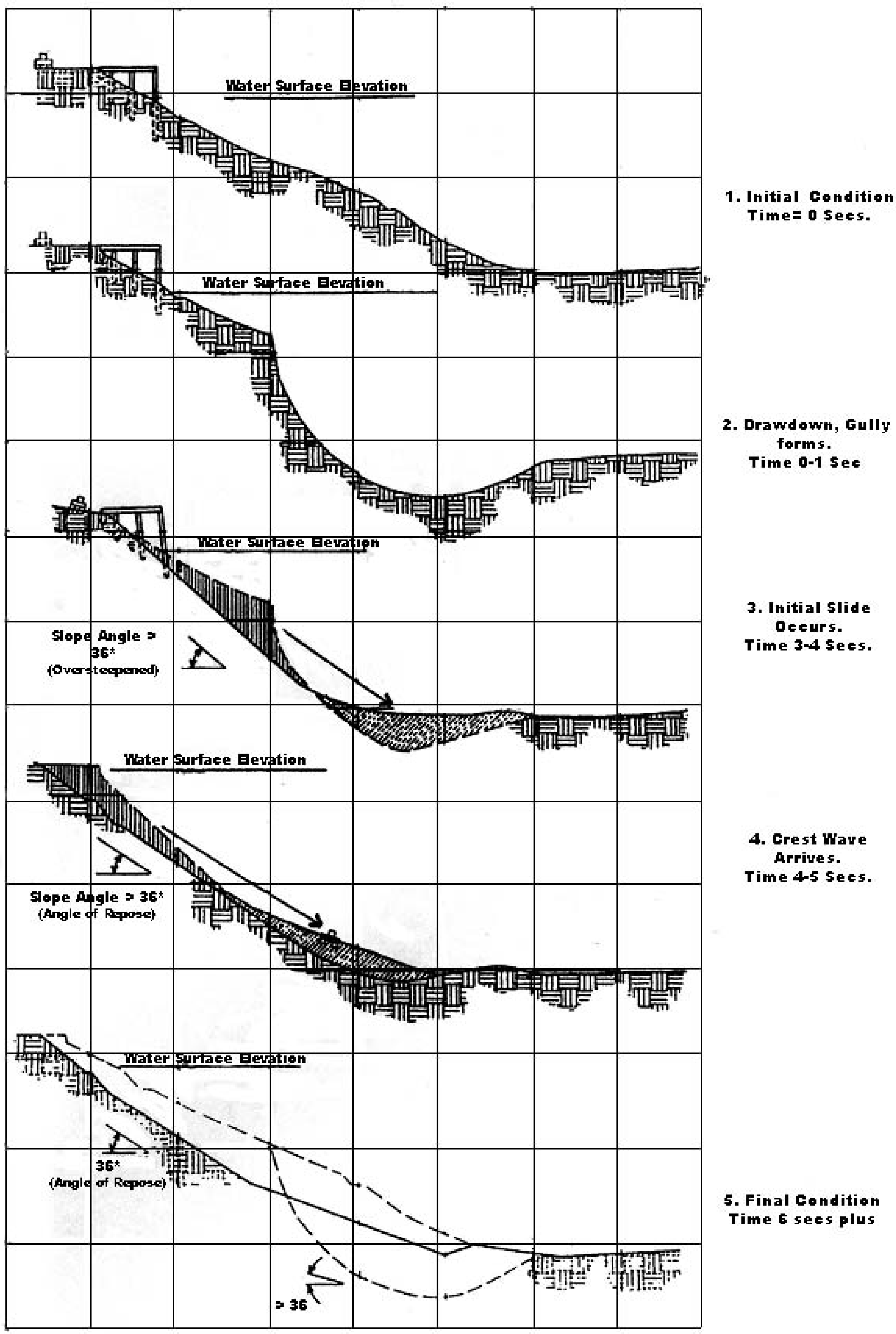

Figure 2.12: Profile of the Landslide that triggered the 3 November 1994 Skagway (Alaska)Tsunami. (Campbell, B. and Nottingham, D., [1999])

2.3.3 Historical tsunamis triggered by volcanic eruptions

One of the most destructive tsunamis due to volcanic eruptions that humanity has experienced was triggered by the 26-27 August 1883 Krakatau (Indonesia) eruption. According to the historical information, there were 3 explosions within 4.5 hours and all of them triggered tsunamis. The first two explosions generated local tsunamis that affected the Sunda Strait (see figure 2.13) whereas the last one caused a distant tsunami. The first explosion occurred when the 130-meter peak of Perboewatan (Indonesia) collapsed forming a caldera, which was filled with seawater generating a tsunami. About an hour later, the second explosion occurred due to the collapse of the 500-meter peak of Danan (Indonesia), this time the tsunami was triggered when seawater filled the magma chamber. Finally, the third and strongest explosion destroyed the Rakata Island (Indonesia), ejecting about 9 to 10 km^3 of rock, spreading around 18 to 21 km^3 of pyroclastic deposists forming a 11.5 km^3 caldera. These explosions caused several tsunami waves that reached as much as 37 m whose inland penetration was larger than 3 km destroying 250 villages in Indonesia. Due to the atmospheric pressure caused by the explosion, long waves were also recorded in Japan, San Francisco, France and England Coasts. (Bryant, E., [2001], Beget, J. [2000] and Tsunami, earthquakes, hurricanes, volcanic eruptions and other Natural and Man-made hazards and disasters [http://www.drgeorgepc.com/Tsunami1883Krakatoa.html]).

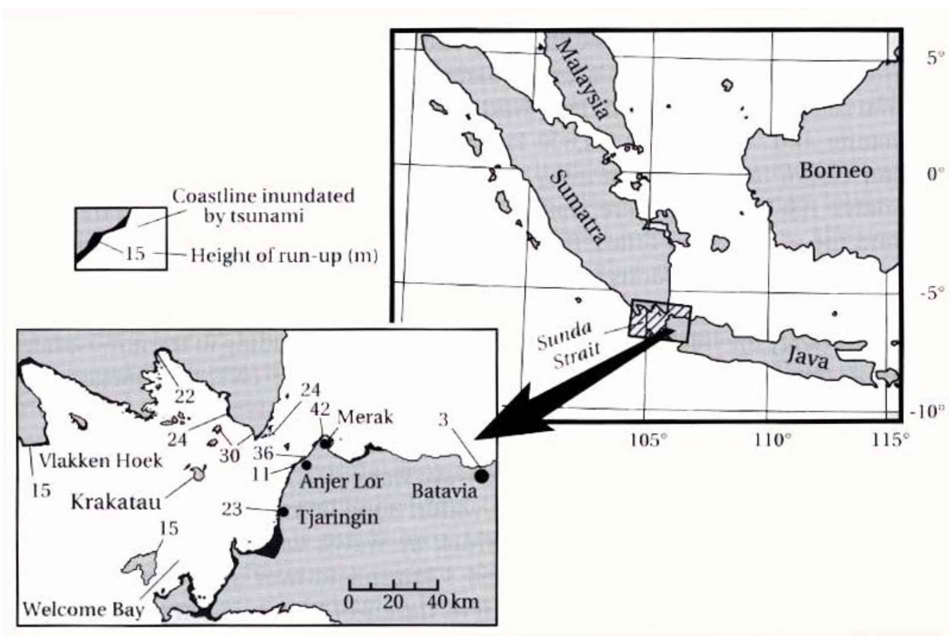

Figure 2.13: 26-27 August 1883 Krakatau Tsunami (Indonesia).

(Bryant, E., [2000])

2.3.4 Historical tsunamis triggered by meteorites

Despite the fact that meteorites collapsing with the Earth are rare events, and that no historical tsunamis triggered by them have ever been recorded, two craters formed by meteorite impact associated with tsunamis have been discovered. Simulation models have been used to estimate the effect of those impacts with the Earth, including tsunami generation. The most famous of those impacts is the Cretaceous-Tertiary extinction event or Chicxulub (Mexico) event that is believed caused the extinction of the dinosaurs. A more recent event that occurred near South America has been also discovered. Some details regarding the tsunamis caused by these events will be given in the sequel (Bryant, E., [2001]).

The Cretaceous-Tertiary extinction event was caused by a meteorite that impacted the Mexican Gulf. The diameter of the meteorite is estimated to have been about 10 to 15 km in diameter. The diameter of the crater formed is about 180 km. Once the meteorite collided with the Earth's surface, seismic waves of surface magnitude (M_s) about 9 to 11 caused the formation of faults in shallow water and submarine landslides occurred in steep slopes around the Mexican Gulf. Soil deposits of up to 9 m containing sand have helped to detect the areas affected by the tsunami generated by the impact, see Fig. 2.14. Simulations conducted by means of numerical models indicated that tsunami waves would have been around 400m height at distances of 1000 km from the source if the meteorite had impacted the ocean (Bryant, E., [2001]).

Another crater has been found 700 km off the southwest corner of South America, this is called the Eltanin Meteorite event. It is believed that this event occurred in the Pliocene Era around 2.15 million of years ago when a 4-kilometre diameter meteorite impacted the Earth and triggered a tsunami. Deposits of marine organisms mixed with terrestrial mammals found along the Peruvian coastline are evidence that the tsunami occurred. Using numerical simulation the estimated tsunami run-up values reached about 30 m in South America and Antarctica whereas in Japan, California and New Zealand these values could have been 4, 10 and 20 m respectively (Bryant, E., [2001]).

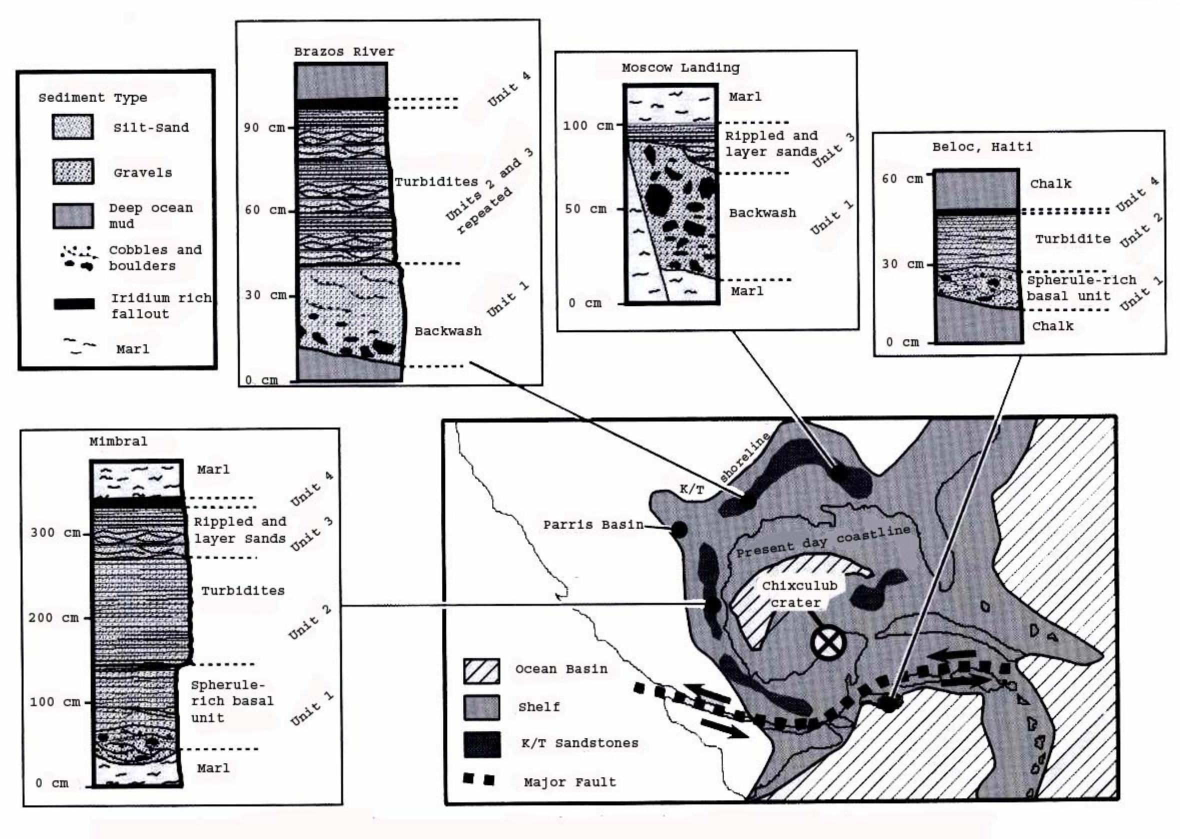

Figure 2.14: Soil profiles that proved the occurrence of the Chixculub event.

(Bryant, E., [2000])

3. GEOLOGICAL SETTING OF EL SALVADOR

3.1. OVERVIEW

El Salvador is located in the Pacific coast of Central America. Lying on the Caribbean plate at the boundary with the Cocos plate, the country is exposed to frequent seismic activity, sometimes very destructive as the 10 October 1986, the 13 January and 13 February 2001 events demonstrate. The Salvadoran seismic activity is complex. Earthquakes are usually associated (depending on the location and the focal depth) with the *Wadati-Bernioff* [7]zone or Upper-Crustal seismic activity in the Caribbean Plate.

Geologically speaking, Central America can be divided in northern and southern Central America. Guatemala, Honduras, El Salvador and northern Nicaragua can be included in the northern portion, whereas southern Nicaragua, Costa Rica and Panama are considered the southern portion. Northern Central America has a continental style crust and it contains Palaeozoic or older rocks and sediments from the upper Palaeozoic, the Mesozoic and the Tertiary. A Cretaceous type crust composes the southern portion, and it has on top thick marine and tertiary volcanic sediments. This portion is, at the moment, a transition zone from pure oceanic to continental crust (Bommer, J. and Rodriguez, C., [2002]).

3.2. TECTONIC FEATURES

The Pacific coast of Central America runs parallel to the Middle America Trench, which is the zone where the Cocos plate subducts beneath the Caribbean plate. It has been established that the incoming plate along the Middle America trench was formed at similar ages although its morphology changes dramatically along the strike. The region is characterised by a smooth slope at the Nicaraguan coast, a very steep slope in Guatemala and a transition zone along the Salvadoran coast. The smooth slope is built of en-echelon terraces, whereas the steep slope contains several canyons and gullies. The transition zone can be described as rough terrain variable in width (Ranero, C., et al [2004]). Figure 3.1 shows approximate locations of tectonic plate boundaries in Central America.

At the Caribbean coast, Northern Central America's geomorphology is characterised by sierras formed of several sub-parallel ranges, composed of metamorphosed deposits, separated by faults and grabens. At the Pacific coast, volcanic ranges and plateaus are located in Nicaragua, El Salvador and parts of Honduras and southwest Guatemala (Bommer, J. and Rodriguez, C., [2002]).

There are basically three seismogenic sources at northern Central America. First the Cocos-Caribbean subduction zone, that produces the largest earthquakes in the region, and the Cocos-North American convergence zone. Second the North America-Caribbean interaction zone and third

[7] Wadatti-Berniof zones are inclined planes where source points of earthquakes occurring in subduction zones are located. This planes can go as deep as 600 km below the Earth free surface.

the upper crust seismicity along the quaternary volcanoes, as shown if Fig. 3.2. Southern Central America's seismicity is due to the interaction of four main tectonic plates and several microplates at their boundaries (See Fig. 3.2).

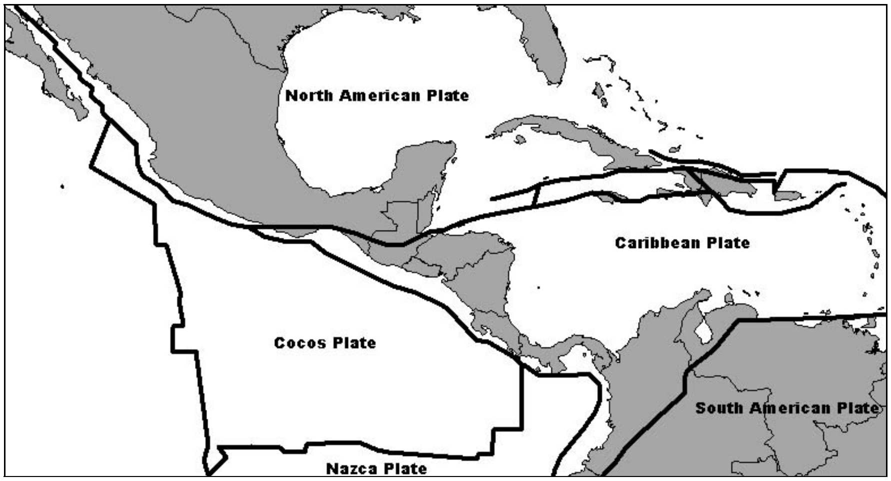

Figure 3.1: Tectonic Plates of Central America.

The subduction zone of Central America can be classified as intermediate, if compared with the *Mariana* and *Chilean* style. The Mariana subduction zone is characterised for having a very sharp dip with a highly extensional overriding zone (see Fig. 3.3) whereas the Chilean subduction zone presents a shallow dip and highly compressional overriding zone (see Fig. 3.4). The Central American trench is considered an intermediate stage between those subduction zones. It has a steep dip that shallows from south Nicaragua to north Guatemala and the overriding zone (the Caribbean Plate) is slightly extensional (Dewey, et al. [2004]).

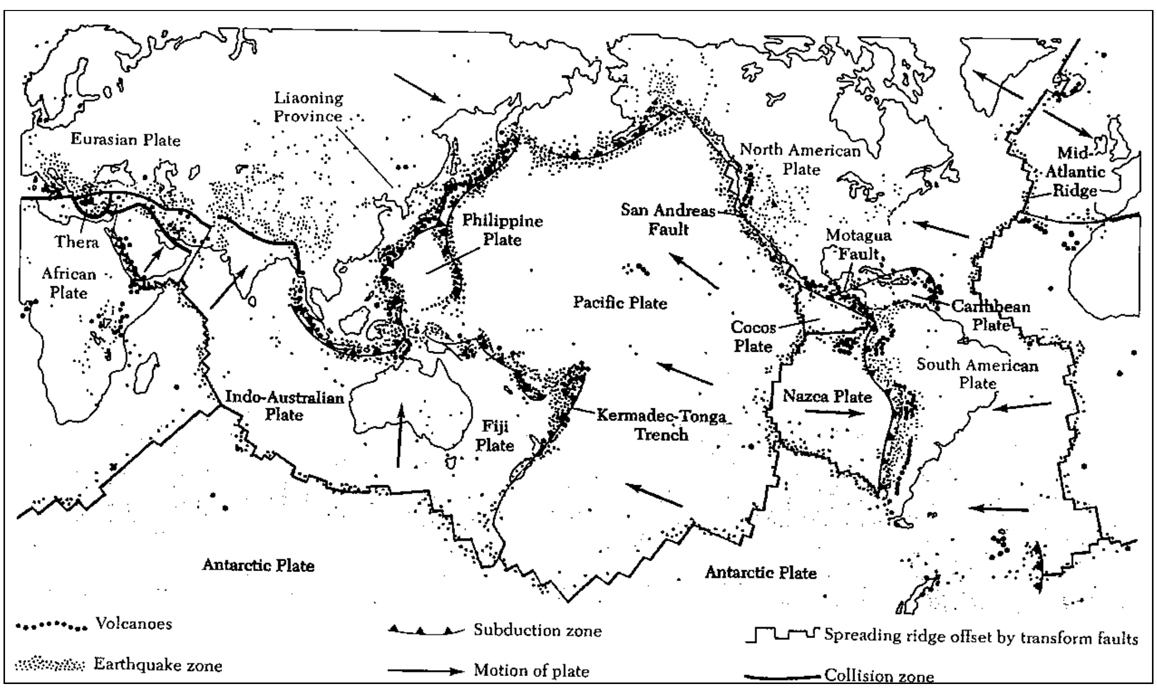

Figure 3.2: Tectonic Plates of the world.

(Fowler, C. M. R., [1990])

El Salvador experiences frequent seismic activity that is associated to its vicinity to the Cocos-Caribbean subduction zone, the upper crustal seismicity within the Caribbean Plate and sometimes to volcanic activity (see Fig. 3.2). Some of the earthquakes occurred at the volcanic front have been very destructive. For example, the 13 February 2001 and 10 October 1986 were shallow-focus events occurring directly underneath population centres and with magnitudes relatively small of M_w 6.6 and m_b 5.4 produced intensities of VIII and VII near the epicentre (SNET, [www.snet.gob.sv]). Subduction zone earthquakes have also been very destructive, the 13 January 2001 earthquake reached a Ms 7.6 and intensities varying from VIII to V were registered across the country (SNET, [www.snet.gob.sv]).

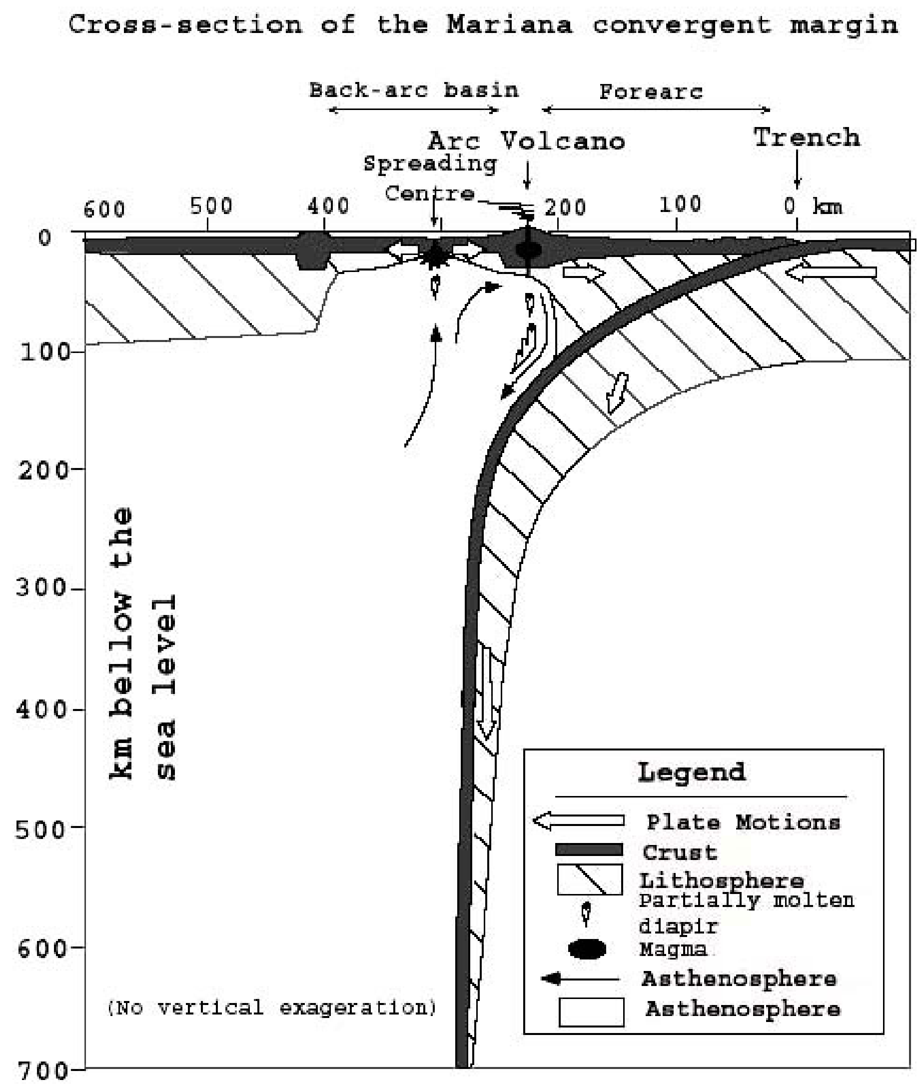

Figure 3.3: Mariana type Subduction Zone.

[http://www.margins.wustl.edu/Eugene.html]

Earthquakes related to the subduction zone can occur within the Wadati-Bernioff zone or at the interface thrust zone. Wadati-Bernioff earthquakes have focal depths varying from 70 to 100 km, being the largest the ones that occur shallower. Interface thrust zone earthquakes have focal depths less than 100 km and occur within 50 to 170 km from the trench axis. Around 60% of them have had Moment Magnitude M_w greater or equal to 6 (Dewey, et al, [2004]).

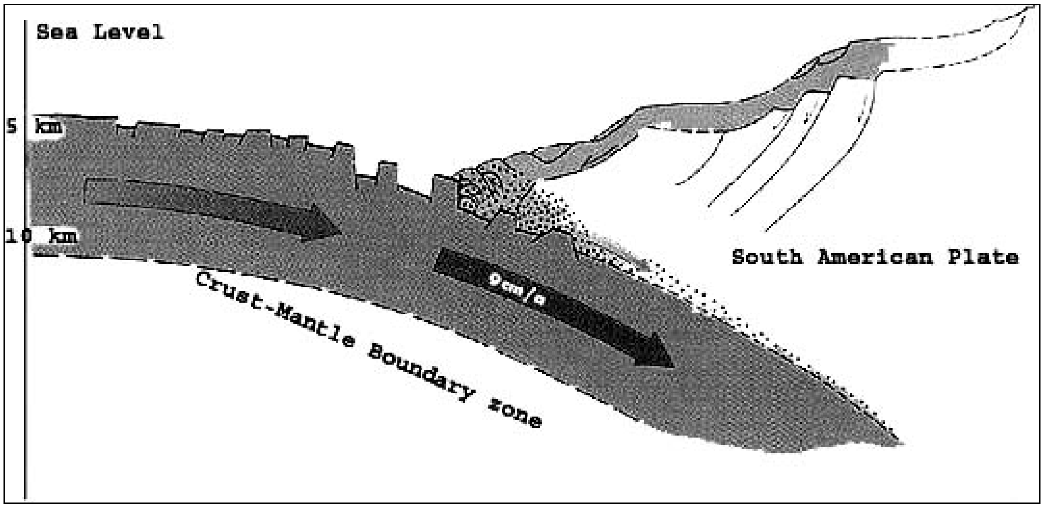

Figure 3.4: Chilean type Subduction Zone.

[http://www.margins.wustl.edu/Eugene.html]

Upper-crustal seismicity within the Caribbean Plate is characterised by earthquakes whose focal depths are commonly less than 15 km but sometimes those depths can be less than 10 km. Strike-slip focal mechanisms are associated to these seismic events, they can be right-lateral in faults almost parallel to the volcanic chain or left-lateral in faults approximately perpendicular to the volcanic chain, as shown in Fig. 3.5. Earthquakes due to upper-crustal activity at the Caribbean Plate are typically preceded by foreshocks or occur in clusters of several events spaced closely in time and space. There are specific locations that have been affected in several occasions, at different times (Dewey, et al, [2004]).

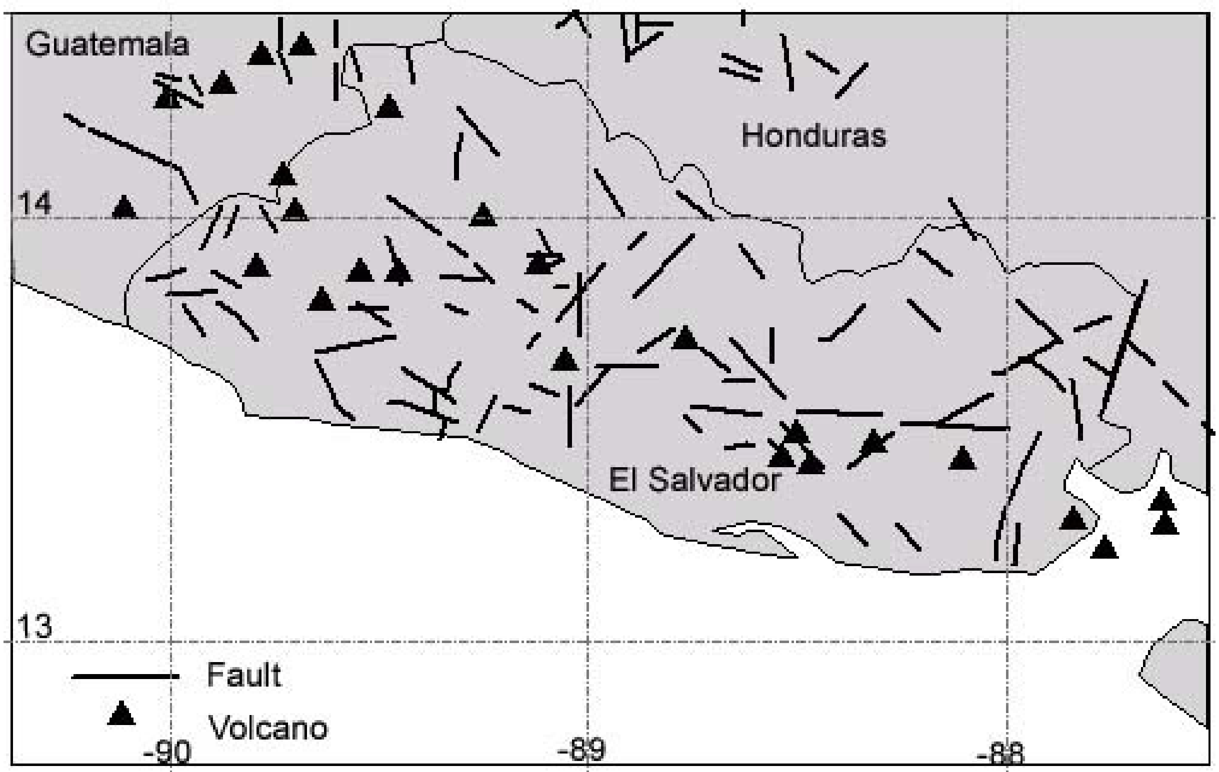

Figure 3.5: Gelogical faults in El Salvador.

(Dewey, et al [2004])

Volcanic earthquakes in El Salvador usually have surface wave magnitudes (M_s) less than 5, they occur as tremors preceding a volcanic eruption, a few minutes or several days can pass between one tremor and the next. Tremors typically occur in clusters (or swarms) close in time and space, and generally the last event has the highest magnitude. This type of seismic activity occurs due to the degassing of magma or boiling of the volcano hydrothermal system (Dewey, et al, [2004]).

3.3. BATHYMETRY OF THE SALVADORAN COAST

Bathymetry is the charting of seafloor topography. It describes the shape and slopes of the seabed and generally is expressed as contour lines called *isobaths* (UNESCO, [1991]). Acoustic sound is often used to map the seafloor bathymetry. In general terms, a transducer transmits and receives sound waves that are recorded by the echosounder that registers data in either digital or analogical format. The data need to be calibrated according the tidal activity of the area and finally the isobaths are drawn commonly using Geographical Information System (GIS) software, which allows drawing graphical information geographically referenced.

Bathymetry is crucial when tsunami modelling is implemented since the run-ups and velocity of the tsunami waves depend on the shape of the seafloor. When numerical simulation is implemented, a very precise description of the seafloor is needed to get accurate results. Some organisations such as the National Oceanic and Atmospheric Administration (NOAA) and The United States Geological Survey (USGS) provide worldwide bathymetric information at different levels of resolution. For more details see the USGS website http://walrus.wr.usgs.gov/infobank/gazette/html/bathymetry/cam.html, and the NOAA website http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html.

Nowadays, very few precise bathymetry data is available for Central America. This is likely to be due to lack of adequate equipment in the region and the high cost of producing high resolution seafloor mapping (Pullinger, C., [written communication]). There are however some institutions that provide on line medium resolution bathymetric maps of Central America, such as the USGS (http://walrus.wr.usgs.gov/infobank/gazette/html/bathymetry/cam.html), and NOAA (http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html). The USGS website provides bathymetric maps that can be freely downloaded as picture format (.jpg) whereas the NOAA website sells a certain number of bathymetry maps. Figure 3.6 shows the topography and bathymetry of Central America; a drastic change of depth at the Middle American Trench can be observed from southern Mexico down to northern Costa Rica at the Pacific Coast of the region.

3.3.1.1 Digital Bathymetric Data of El Salvador

As mentioned before, finding high resolution digital bathymetric data of Central America including El Salvador is difficult at the moment (Pullinger, C., [written communication]). There is a project sponsored by the National Oceanographic and Atmospheric Administration (NOAA) and the Institution of Oceanography La Jolla called “Global Sea Floor Topography from Satellite Altimetry and Ship Soundings” that has mapped the zone and that provides free information in digital format. The project aimed to create “a digital bathymetric map of the oceans with horizontal resolution of 1 to 12 km that was derived by combining available depth soundings with high-resolution marine gravity information from de Geosat and ERS-1 spacecraft[8].” (http://topex.ucsd.edu/marine_topo/Science.html).

Topographic and geodesic data of the world, obtained from the Global Sea Floor Topography from Satellite Altimetry and Ship Soundings, can be downloaded for free at the website

[8] Spacecrafts are vehicles manned or unmanned which travel in space, generally orbiting the Earth.

http://topex.ucsd.edu/cgi-bin/get_data.cgi. People are allowed to use that information as they consider appropriate. In order to get the data, one must specify the coordinates of a rectangular area and download a file, which contains three columns with the longitude, latitude and elevation of some points located in the rectangular area.

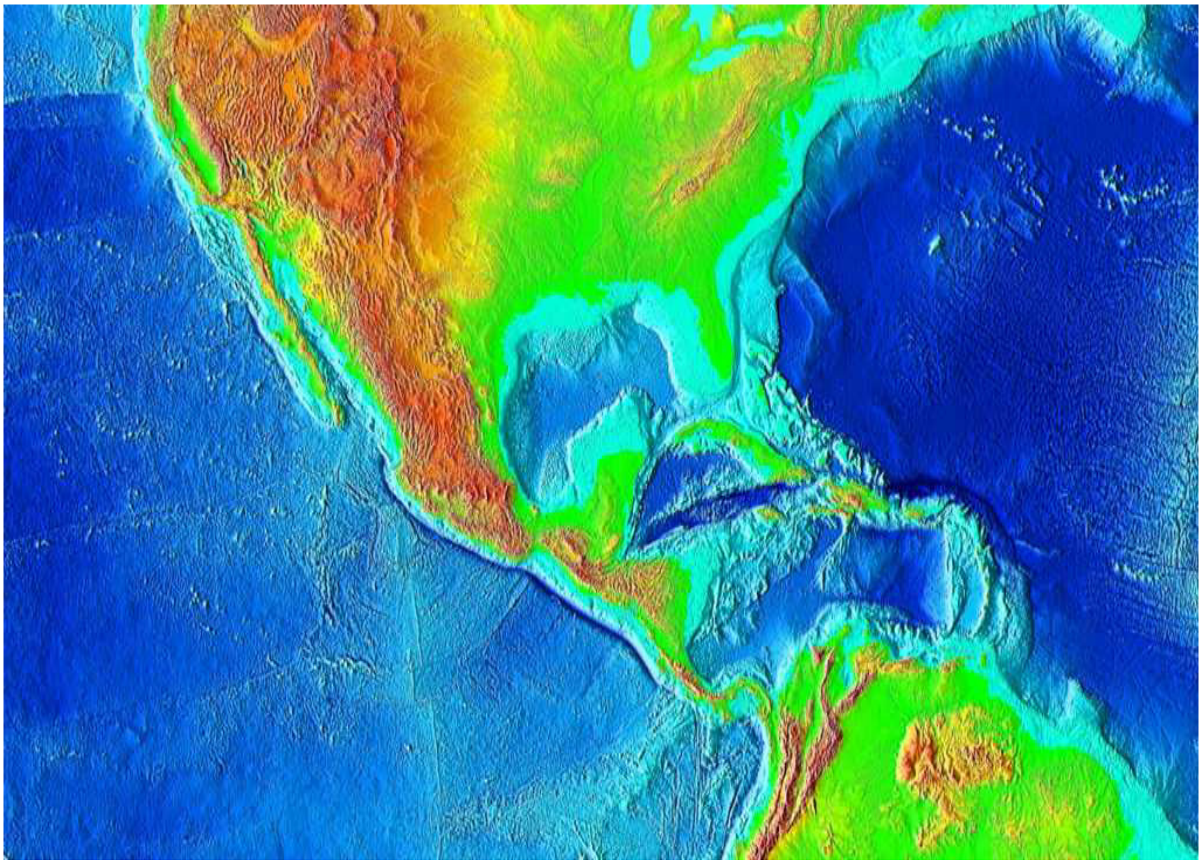

Figure 3.6: Bathymetry and topography of Central America.

[http://www.ngdc.noaa.gov/mgg/image/2minrelief.html]

Using the data provided in the previous mentioned website, isobaths of El Salvador were drawn as shown in Fig. 3.7. The figure shows the sharp change in the seafloor depth (from –500m to –1000m) that goes approximately parallel to the coastline of the country. The map was drawn by selecting points of similar elevation and joining them with lines. It is important to emphasize that such information is not very precise, but can help to have a gross idea of the coastal bathymetry of the country.

3.4. RELEVANT TSUNAMIGETIC SOURCES

Tsunamis are not considered a major hazard in Central America, people are not aware of that risk and recent tsunami events recorded in the area have been forgotten. Despite this situation, studies on this topic have started to emerge after the September 1992 Nicaraguan tsunami and they show that the region is a moderate tsunamigenic zone.

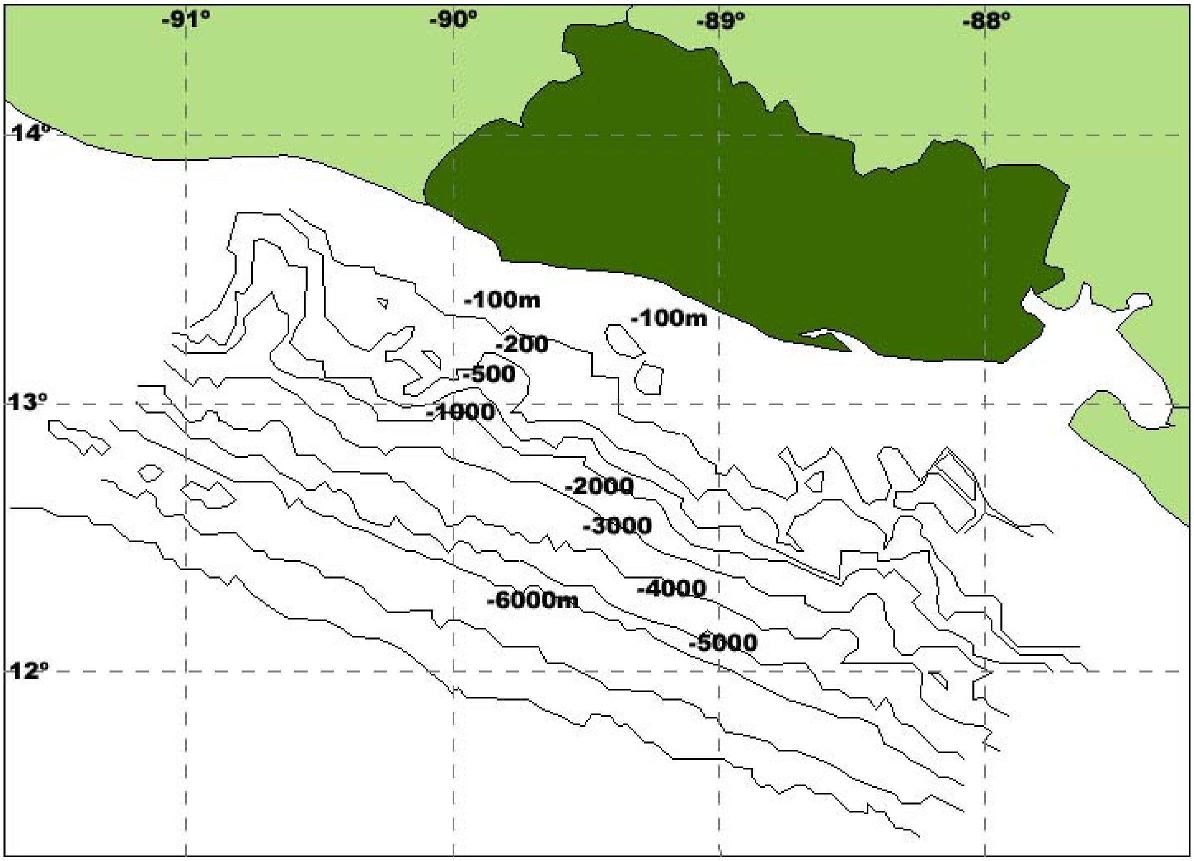

Figure 3.7: Isobaths of the Salvadoran Coast, created with data from Global Sea Floor Topography from Satellite Altimetry and Ship Soundings.

Forty-nine tsunamis have been registered at Central American coasts between 1539 and 1998; thirty-seven of them have been recorded at the Pacific Coast and 12 at the Caribbean Coast (Molina, E., [1997]). Six of the tsunamis registered in the Pacific where associated to unknown cause, the rest were associated to earthquakes occurred at the Cocos-Caribbean subduction zone, Panama fracture zone, North American-South American plates boundary or due to shallow faults. All of the tsunamis registered at the Caribbean coast were associated to earthquakes. (Fernandez, M. [2000]).

Preliminary studies have established that Central America is a moderately *tsunamigenic zone* and that is affected mainly by tsunamis triggered by earthquakes. Tsunamis associated to submarine landslides, terrestrial landslides or volcanic eruptions have not been reported in the area. Submarine eruptions are not a possible tsunamigenic source in the region, given the fact that there are no active submarine volcanoes in the area. However, it is possible that one of the inland volcanoes located in Nicaragua (The Cosigüina Volcano) triggered tsunamis. (Fernández, M. [written communication]).

El Salvador has been struck by 11 tsunamis, all of them triggered by earthquakes; none of them has been associated to landslides (Fernández, M., et al [2004]). As mentioned before, submarine volcanoes are not a tsunamigenic source in the area. Since inland volcanoes of El Salvador are far away from the coast, eruptions are unable to trigger tsunamis. However, debris avalanches caused by eruptions or collapse of inland volcanoes could have caused a tsunami in the late Pleistocene age (Siebert, et al, [2004]). In 1951, tsunami waves caused by a strong earthquake that split the dormant Cosigüina Volcano in Nicaragua (Molina, E., [1997]) could have hit the Salvadoran coast (Fernández, et al, [2004]), see section 3.4.2.

3.4.1 Earthquakes

Seismic activity is very frequent and some times very damaging in El Salvador. Major earthquakes with M_s magnitude between 5 and 7.7 (Dewey et al, [2004]) are expected to occur within 10 years approximately (Rose et al, [2004]). These events have triggered landslides and tsunamis. In fact, all of the tsunamis registered in the country have been directly associated to seismic events.

Eleven tsunamis have been recorded in the country from 1859 to 1997, two of them occurred in the XIX century whereas nine were reported during XX. That leads to conclude that some tsunamis occurred before the XIX century might have been unreported due to the fact that they occurred in uninhabited zones at that time. Another cause of the low rate of tsunamis reported in the XIX century could be that they were very small that passed unnoticed because the lack of equipment to measure them (Molina, E., [1997]). Tsunami catalogues for the region will be approached in chapter 5.

Five out of the 11 tsunamis reported were due to local earthquakes, 3 tsunamis were due regional earthquakes and 3 were due to distant earthquakes. Damage due to tsunamis in El Salvador varied depending on the location of the triggering earthquakes. Events triggered by local earthquakes have been more severe than those triggered by regional or distant earthquakes. Damages reported include flooding and destruction of villages (Fernández, M., et al [2004])

Local tsunamis:

Mainly inland earthquakes located near the shoreline have triggered local tsunamis in El Salvador (see Fig. 3.8). Table 3.1 shows the tsunamigenic earthquake parameters, as it can be seen some of the earthquakes have had values of surface magnitude M_s as small as 6.

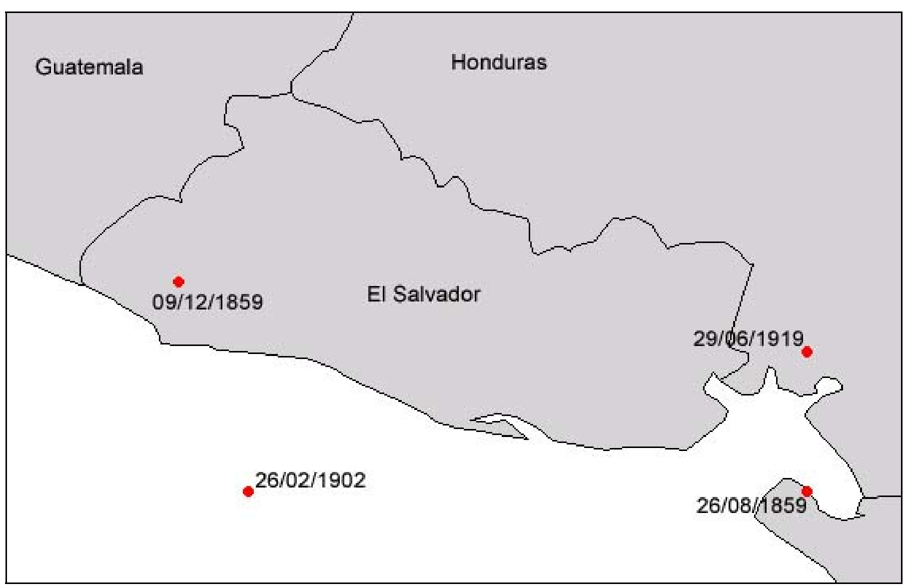

Figure 3.8: Earthquakes that triggered Local Tsunamis in El Salvador between 1539 an 1996. (Fernandez, et al. 2004).

Table 3.1: Local Tsunamigenic earthquakes in El Salvador.

(Fernandez, et al. 2004)

			Earthquake parameters				
No	**Date**	**Time**	**Elat**	**Elong**	**Ed**	**Em**	**Tsunami Location**
1	1859	0826	13	-87.5	ND	6.2	Gulf of Fonseca
2	1859	1209	13.75	-89.75	40	7	Acajutla
3	1902	0226	13	-89.5	30	7	Garita Palmera
6	1919	0629	13.5	-87.5	40	6.7	Gulf of Fonseca
8	1950	1023	14.3	-91.8	S	7.3	Gulf of Fonseca

Elat Earthquake latitude
Elong Earthquake longitude
Ed Earthquake depth
Em Earthquake magnitude (M_s)
ND No data
S Shallow

Local tsunamis have been the most destructive events, they have all together caused around 200 deaths. The most remarkable tsunamis are those occurred in August 1859 and February1902. The 1859 tsunami affected La Union (see Fig. 3.9) where damages to houses and boats were reported and some vessels sank. The second event affected fiercely Acajutla (see Fig. 3.9). This was a noisy tsunami with noticeable withdrawing of the seawater, it had three waves that washed houses and trees to the ocean. In beaches located within 120 km, flooding extended for about 100 m. The height of the 1902 tsunami waves were not measured, but it is estimated that they could have reached about 20 meters (Fernández, M., et al [2004] and Larde y Larin, J. [2000]).

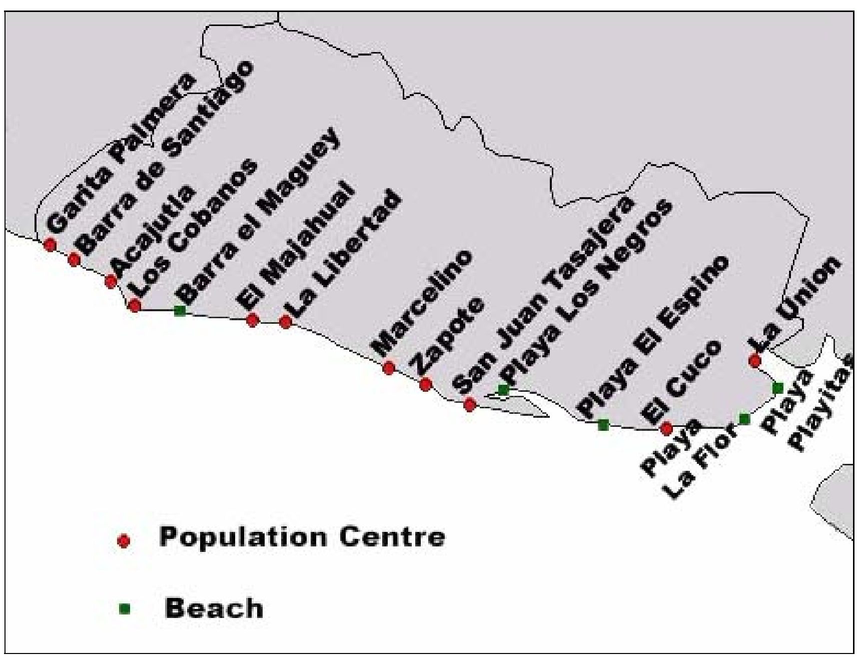

Figure 3.9: Population Centres at the Coast of El Salvador.

(Fernández, M., [2000])

Regional tsunamis:

Three regional tsunamis have been recorded between 1859 and 2001. They have been triggered by earthquakes occurred in Guatemala and Costa Rica, both in 1950, and in Nicaragua in 1992. All of these earthquakes had surface magnitudes M_s greater than 7. The three regional tsunamis affected the whole Salvadorian coast since they were recorded all around the Pacific Ocean (See Fig. 3.10). The Guatemalan and Costa Rican tsunamis were very small even near their sources, the Nicaraguan event, on the other hand, was very destructive in Nicaragua but very small when it reached the Salvadorian coast (Fernández, M., [2004]). The earthquake parameters are shown in table 3.2.

Table 3.2: Regional Tsunamigenic earthquakes in El Salvador.

(Fernandez, et al. 2004)

			Earthquake parameters				
No	**Date**	**Time**	**Elat**	**Elong**	**Ed**	**Em**	**Tsunami Location**
7	1950	1005	10	-85.7	60	7.7	The entire Coast
8	1950	1023	14.3	-91.8	S	7.3	Gulf of Fonseca
11	1992	0902	11.7	-87.4	S	7.2	Gulf of Fonseca

Elat Earthquake latitude
Elong Earthquake longitude
Ed Earthquake depth
Em Earthquake magnitude
ND No data
S Shallow

Distant tsunamis:

Three pacific-wide tsunamis have been recorded in El Salvador throughout history. The 1906 Colombian event, the 1957 Alaskan tsunami event and the 1960 Chilean. The most destructive event of this kind is the 1957 Alaskan tsunami that struck Acajutla (see Fig. 3.11) where several meter height waves were reported. Although the Colombian and Chilean tsunamis were triggered closer to the country, only small waves were reported. Both tsunamis affected the entire Salvadorian coast (Fernández, M., [2004], Lardé y Larín, [2000]).

Table 3.3: Distant Tsunamigenic earthquakes in El Salvador.

(Fernandez, et al. 2004)

			Earthquakes parameters				
No	**Date**	**Time**	**Elat**	**Elong**	**Ed**	**Em**	**Tsunami Location**
4	1906	0131	1	-81.3	ND	8.1	The entire Coast
9	1957	0310	51.63	-171.4	ND	8.1	The entire Coast
10	1960	0522	38.2	-73.5	32	8.5	The entire Coast

Elat Earthquake latitude
Elong Earthquake longitude
Ed Earthquake depth
Em Earthquake magnitude
ND No data
S Shallow

The reason why the Colombian and Chilean events were not very destructive has to do with the direction of propagation of the tsunami, that focus their energy in other directions. This is also related to the type of rupture produced by the triggering earthquake (Bryant, E. [2001]). The earthquake parameters are shown in table 3.3.

3.4.2 Volcanic Eruptions

Inland or submarine volcanic eruptions can trigger tsunamis through different processes and depending on their location and amount of ejected or transported material, as mentioned in Section 2.2.3. There are no active submarine volcanoes in El Salvador and its active inland volcanoes are not close to the ocean.

Volcanic tsunamis have not been directly recorded in El Salvador; however, recent studies revealed that a debris avalanche occurred in the western part of the country in the late quaternary age could have caused a tsunami. The avalanche was caused by the eruption of the Santa Ana volcano and it travelled around 500 km to the Pacific Coast as shown in Figure 3.12. Geological and topographical data analyses lead to the fact that the avalanche reached the sea. The volume of volcanic material that was estimated to have been deposited in the sea is 16± 5 km^3, if that was the case, it is very likely that a tsunami was triggered (Siebert, L., et al, [2004]).

There is also a dormant Nicaraguan volcano located near the Gulf of Fonseca (see Fig. 3.9) that is supposed to have triggered a tsunami that affected Honduras and Nicaragua in 1951. The volcano had been inactive since 1835 but an M_s 6 earthquake (in August, 1951) produced a split of its sides that opened up throwing tons of water, contained in its crater, that flooded a small port called Potosi near the Gulf of Fonseca. These tsunami waves affected also Honduras (Molina E., [1997] and Fernández, M., et al, [2004]). If a similar phenomenon occurred, El Salvador is likely to be hit by those tsunami waves.

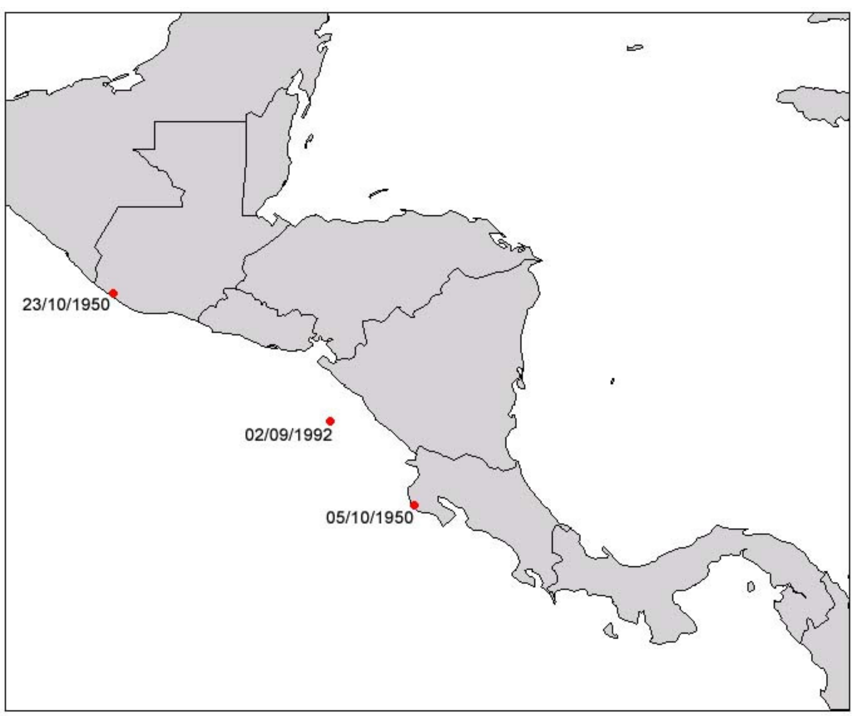

Figure 3.10: Earthquakes that triggered Regional Tsunamis in El Salvador between 1539 and 1996.

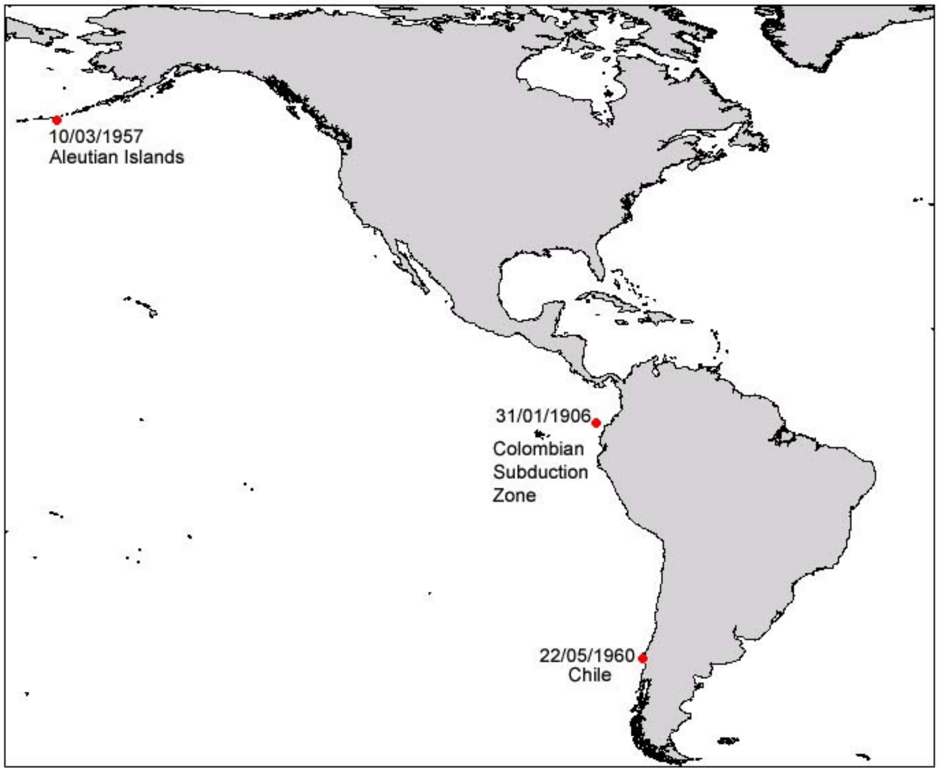

Figure 3.11: Earthquakes that triggered Distant Tsunamis in El Salvador between 1539 and 1996.

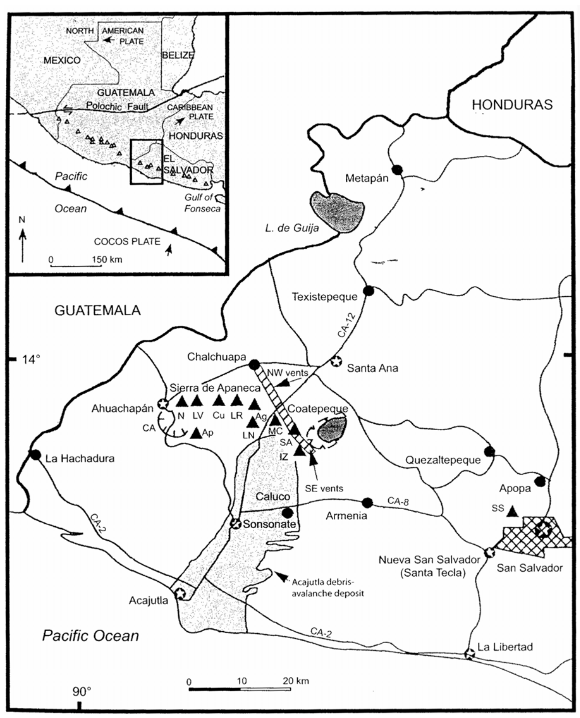

Figure 3.12: Approximate Extent of Debris Avalanche Deposits caused by the Collapse of the Santa Ana Volcano in the Late Quaternary Age.

[Siebert, L., et al (2004)]

4. TSUNAMI HAZARD POTENTIAL OF EL SALVADOR

4.1. OVERVIEW

All throughout its history, El Salvador has experienced natural phenomena such as earthquakes, landslides, floods, mudslides, volcanic eruptions and extreme meteorological events. The most common events are earthquakes associated with the subduction zones or the volcanic chain, which have generated massive landslides or mudslides. Tsunamis are not seen as major hazard in the country because there has not been any destructive tsunami since the beginning of the last century. However, studies have shown that the Salvadoran coast is likely to be hit by tsunamis.

4.2. HISTORICAL RECORDS AND PALEOTSUNAMI DATA

Historical tsunamis are the events that have occurred and been recorded in a region. This kind of records, in Central America, date back from the XVI century. Forty-nine events have been recorded since that time. The number of tsunamis reported has been increasing with time, for example, 4 events were reported between the XVI and XVIII centuries whereas 11 and 35 events were reported during the XIX and XX centuries, respectively. This is due to the fact that population centres have been spreading along the coast, and most importantly because of the improvement of equipment to measure tides and of global communications. In El Salvador, there have been registered 11 tsunamis, the oldest event was recorded in 1859 whereas the most recent was recorded in 1992 (Molina, E., et al [1997]).

Tsunamis identified based on studies of geological deposits are called *paleotsunamis*; these events are identified through analyses and studies of soil profiles that are commonly determined using sound wave propagation techniques. Soil profiles containing marine plants, shell or marine animals mixed with silt, sand or terrestrial soil are considered indirect evidence of tsunamis occurrence. Shape and size of transported material are also considered indirect evidence of tsunamis. Having identified the affected areas, possible tsunamigenic sources have to be identified and numerical simulation could be implemented to find out the *run-up* parameters.

No information regarding paleotsunamis has been gathered in El Salvador so far; a very interesting and helpful project would be studying soil profiles along the Salvadorian coast to identify possible occurrence of paleotsunamis and in that way, have a better tsunami historical record.

4.3. PREVIOUS STUDIES ON TSUNAMI HAZARD

Generally speaking, tsunamis are not considered a major hazard in Central America. People are not aware that they are at risk of being affected by these events, and not even coastal inhabitants of the region know what to do in case a tsunami occurs. It seems that even tsunamis that occurred recently, relatively speaking, have been forgotten (Fernández, et al, [2004]).

Studies on tsunami hazard assessment of Central America started emerging after the Nicaraguan tsunami in September 1992. That event was very destructive along the Pacific Nicaraguan coast, but caused no damage in the rest of the Central American countries. This might have contributed to the little awareness of the rest of the Central American population regarding to tsunami hazard.

Previous studies have established that Central America is a tsunamigenic region where (very) destructive tsunamis have been registered in the past two centuries and that all countries are likely to be hit by tsunami waves in the future. Those documents have shown that the Caribbean coast is less tsunamigenic than the Pacific coast. At the Pacific coast, *empirical tsunami hazard estimation*[9] has found that Nicaragua, El Salvador, and Honduras are the most prone coasts to be hit by tsunamis.

Having established that Central America is vulnerable to tsunamis, *numerical simulation*[10] and *empirical tsunami hazard estimation* approaches have been implemented. The need of implementing a *tsunami warning system* that matches the region characteristics was also proposed.

4.3.1 Empirical Tsunami Hazard Estimation

Once it was found that several tsunamis affected Central America, some studies started to emerge in order to characterise this phenomena. One of the first approaches on the topic was called *empirical tsunami hazard estimation.* The first step of the approach was to identify the probability that earthquakes with M_s greater than 7 could trigger tsunamis. Next step was to identify the most tsunamigenic zones (Fernández, M., et al [2000]).

The *empirical tsunami hazard estimation*[10] consists in a graphical method to find the efficiency of major earthquakes to generate tsunamis in a region through finding the frequency of earthquakes and tsunamigenic earthquakes. The steps that the empirical tsunami hazard estimation requires are the following:

a) Define the region of study, which generally includes the area from the coast to the subduction zone area.
b) Graphically locate the earthquakes whose M_s magnitude is greater or equal to 7.
c) Divide the coastal region into segments, the limits of the segment are chosen trying to find similar seismic characteristics. The limits of the segments are generally the borders of seismic gaps.
d) Find the rate of earthquake occurrence (frequency of earthquakes in the zone). This parameter can be approximately computed by dividing the number of earthquakes occurred at each segment by the total of earthquakes occurred in the region of interest.
e) Draw a two-series bar graph, one to plot the number total number of earthquakes for each segment and the other to plot the number of tsunami earthquakes occurred within each segment. (See Fig. 4.1)
f) Compute the percentage of earthquakes that have generated tsunamis at each segment by dividing the number of tsunamigenic earthquakes by the number of earthquakes occurred within each interval (Fernández, M., et al [2000]).

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[9] Empirical approaches of tsunami hazard were implemented in 2000 by Centro de Investigaciones Geofísicas (CIGEFI) de la Universidad de Costa Rica, the Red Sismológica Nacional (RSN: ICE-UCR) the Instituto of Sismología, Vulcanología, Hidrogeología y Meteorología de Guatemala and the Institute of Solid Earth of the University of Bergen, Norway.

[10] Tsunami numerical simulations were implemented in 2004 by the Central American Seismological Centre (CASC), the Centro de Investigación Cientifica y Educación Superior de Ensenada (CICESE) and the Escuela Centroamericana de Geología de la Universidad de Costa Rica.

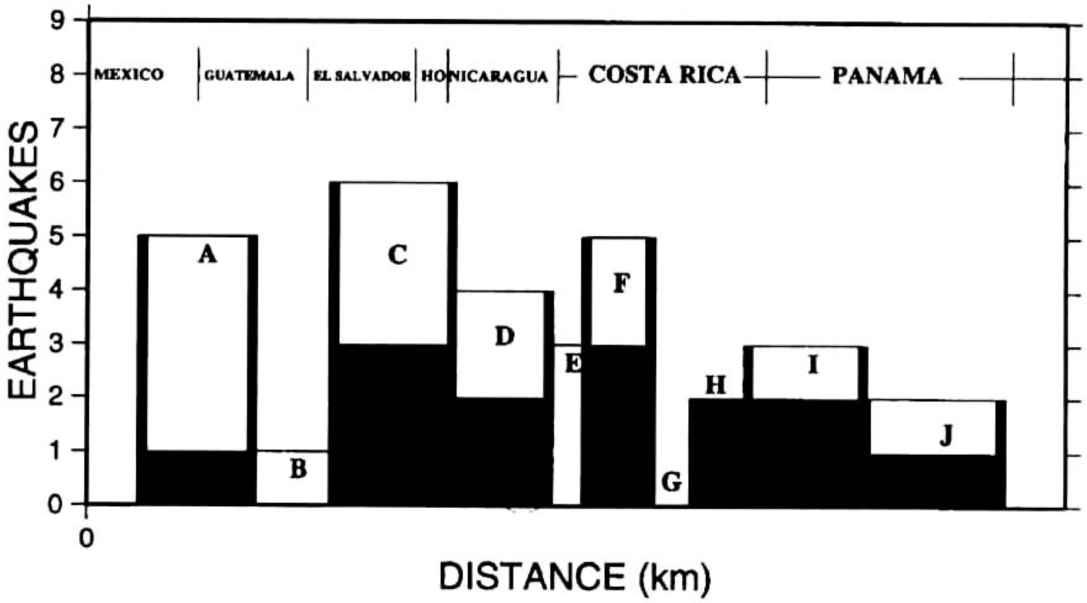


Figure 4.1: Frequencies of Large Earthquakes occurred along the Pacific coast of Central America between 1539 and 1996.

(Fernandez, M., [2000])

An empirical tsunami hazard analysis for Central America was implemented in 2000[10], the results are shown in figure 4.1. The results revealed that 45% of the earthquakes occurred at the Pacific coast of Central America produced tsunamis; 32% of them were concentrated at the coastal segment that goes from Nicaragua to Guatemala. These percentages indicate the efficiency of the earthquakes at triggering tsunamis when occurred at those locations. The values obtained from the analysis are shown in Table 4.1 and Fig. 4.2 (Fernández, et al, [2000]).

Figure 4.2 shows that in regions as Costa Rica and Panama, large earthquakes occur less frequently than in the segment that goes from Nicaragua to Mexico. Table 4.1 indicates that in Costa Rica and Panama those large earthquakes are more efficient at triggering tsunamis. The same pattern was found when the Caribbean coast was studied. Large earthquakes were scarce but all of them caused tsunamis.

According to these results, the coastal segment named "C" in Fig. 4.2 that corresponds to El Salvador and Honduras Pacific coast is the one with the highest number of large earthquakes and also the highest number of tsunamis registered; 50% of those large earthquakes have triggered tsunamis. Coastal segment "A" corresponding to Mexico and Guatemala presents the lowest percentage (20%) of tsunamis triggered by large earthquakes despite the fact that the total of large earthquakes is very high.

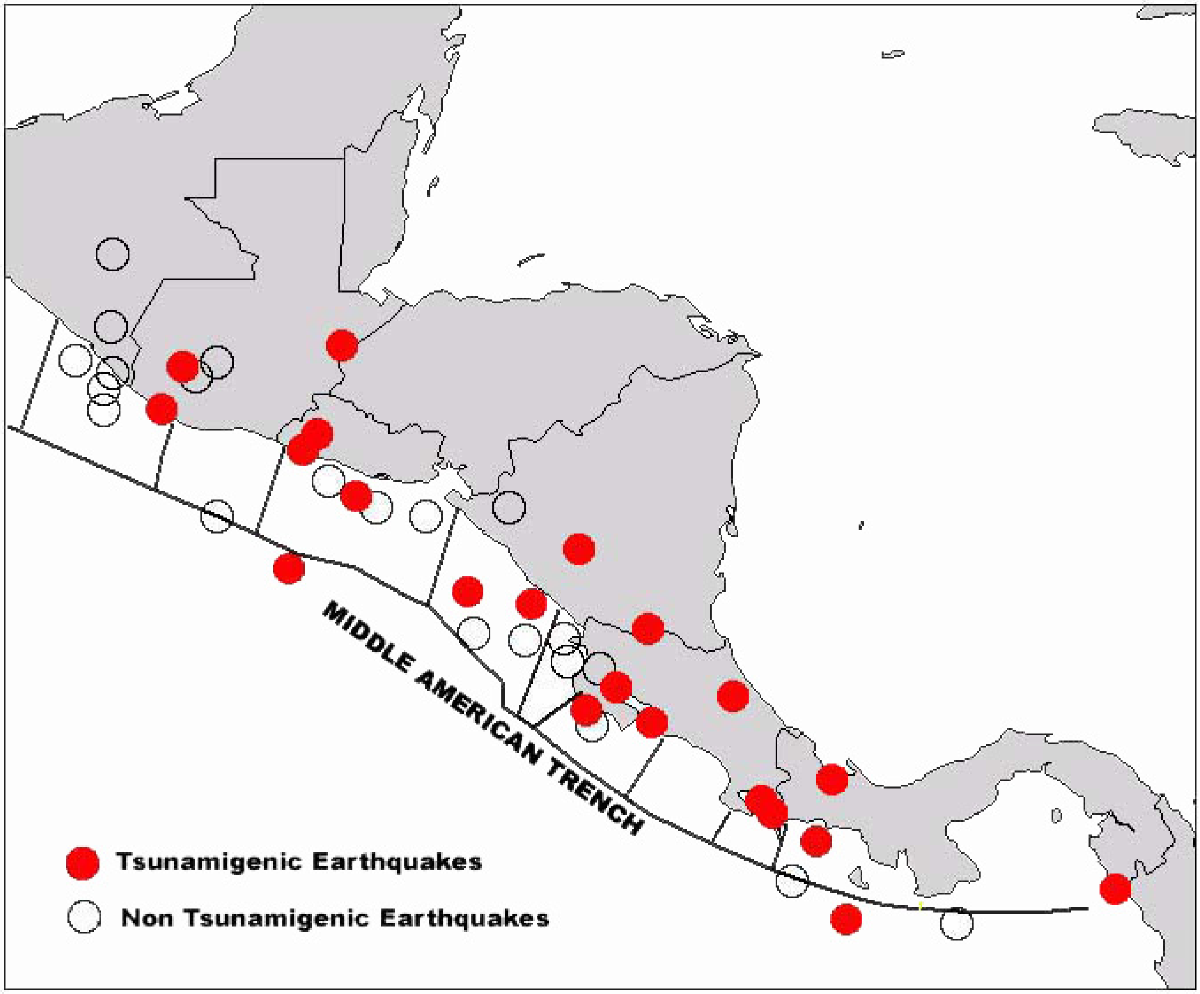


Figure 4.2: Large earthquakes registered in Central America between 1539 and 1996. (Fernandez, M., et al [2000])

Table 4.1: Percentage of Large Earthquakes that triggered Tsunamis in Central America (Fernandez, M., et al [2000])

Segment	Country	Total of Large Earthquakes	Total of Tsunamis	%
A	Mexico-Guatemala	5	1	20
B	Guatemala	1	0	0
C	El Salvador-Honduras	6	3	50
D	Nicaragua	4	2	50
E	Costa Rica	3	0	0
F	Costa Rica	5	3	60
G	Costa Rica	0	0	---
H	Costa Rica	2	2	100
I	Costa Rica-Panama	3	2	67
J	Panama	2	1	50
	Total	31	11	

4.3.2 Numerical simulations

In order to show the potential hazard that large distant tsunamis represent for El Salvador and to increase the awareness towards these events, numerical simulations were implemented[9]. The source chosen was the 31 January 1906 Colombian tsunami that was triggered by an M_s 8.1 earthquake occurred at a place having geographical coordinates 1°N 81.30°W. Figure 3.9 shows the location of this event.

The Tsunami Inundation Modelling for Exchange Program (TIME) that has been developed by the Tohuku University, in Japan, was used in this analysis (further information can be found at http://www.tsunami.civil.tohoku.ac.jp/hokusai2/main/eng). The program is based on the use of equations of mass conservation for incompressible fluids and conservation of momentum. The code is based on the following assumptions: shallow water flows when the ratio water depth to wavelength is small, vertical acceleration of water particles is negligible compared to gravitational acceleration, pressure distribution is approximately equal to hydrostatic profiles, vertical motion of particles does not affect pressure distribution and horizontal velocity of water particles is vertically uniform (Fernandez, M., et al [2004]).

The numerical model discriminates between the tsunami propagation in *deep* and *shallow waters*. At deep waters only linear terms are considered in the momentum conservation equation whereas at shallow waters frictional and nonlinear terms are included in that equation. *High resolution bathymetry* is needed when analysing the tsunami behaviour in shallow waters, because as mentioned before, bathymetry can be a determining factor for the amplification or attenuation of run up values (Fernandez, M., et al [2004]).

The seafloor deformation that generated the tsunami was set to be approximately equal to the vertical displacement induced by the earthquake as initial condition of this specific analysis. The variation of seafloor deformation with time was not considered; this is valid when that deformation is large enough if compared with the seafloor depth at the source and when the rupture velocity is short in relation to the tsunami propagation velocity (Fernandez, M., et al [2004]).

The vertical seafloor deformation induced by the earthquake was computed using the Mansinha and Smylie (1971) analytical expressions for the internal deformation of a continuous media due to shear and tensile faulting. Fault parameters and rupture mechanism were computed by inversion of seismic data and assumptions of geological parameters. The rupture mechanism was found to be "reverse-slip" the vertical slip was 10m over an area of 400km x 100km, the fault dipped at 30° SE and its depth was 30km. (Fernandez, M., et al [2004]).

The aims of this approach were to get the amplitude and travel time of the front waves, to estimate the run-up height distribution along the Salvadorian coast and to characterise the temporal signature of the tsunami (Fernández, et al, [2004]).

Travel time and wave amplitude obtained from the simulation are presented in Fig. 4.3 that shows tsunami wave fronts in thin lines and maximum heights in thick lines. Figure 4.4 shows the scenario of maximum heights of waves at 50 m depth water at the Central American coast. Run-up height distributions along the Salvadorian coast are shown in Fig. 4.5 and the *temporal signature*[11] of the tsunami at deep and shallow waters is shown in Fig. 4.6 and 4.7 respectively.

[11] Temporal signature is the variation of the vertical run-up with time, it is expressed as a graph of vertical run-up values registered at a fixed point at different times.

Wave-front heights from Fig. 4.3 vary between 0.5m and 1.0m whereas in Fig. 4.4 heights reach values close to 2.0m, that difference is due to the bathymetry amplification effect at shallow waters. The same behaviour is found when comparing the signature of the tsunami at deep water (Fig. 4.6) and the signature at shallow water (Fig. 4.7). Smaller heights rapidly attenuating were estimated at deep waters, while greater heights were computed at shallow waters.

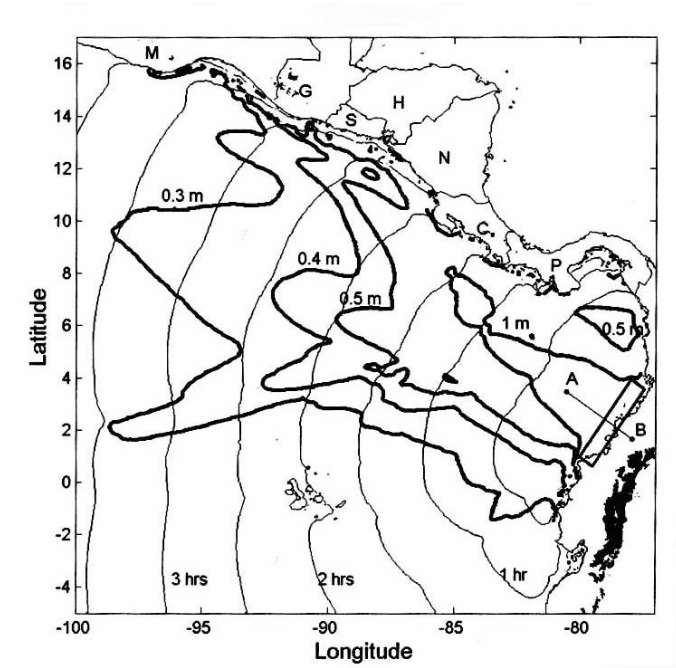


Figure 4.3: Wave front of the 31 January 1906 Colombian tsunami.

(Fernandez, M., [2004])

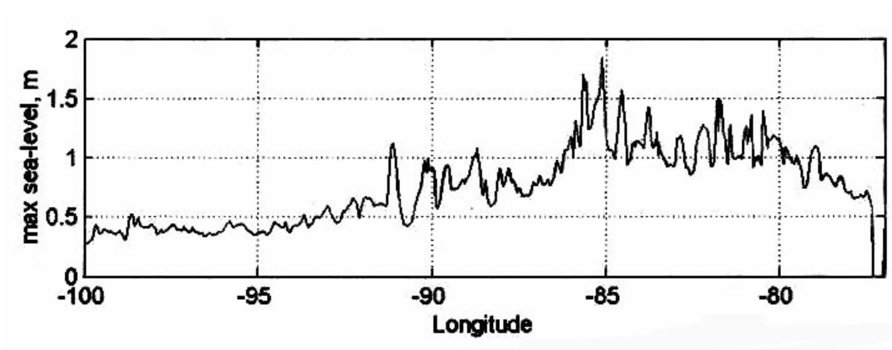


Figure 4.4: Run-up values generated by the 1906 Colombian tsunami at 50-meter deep water offshore the Salvadorean coastline.

(Fernandez, M., [2004])

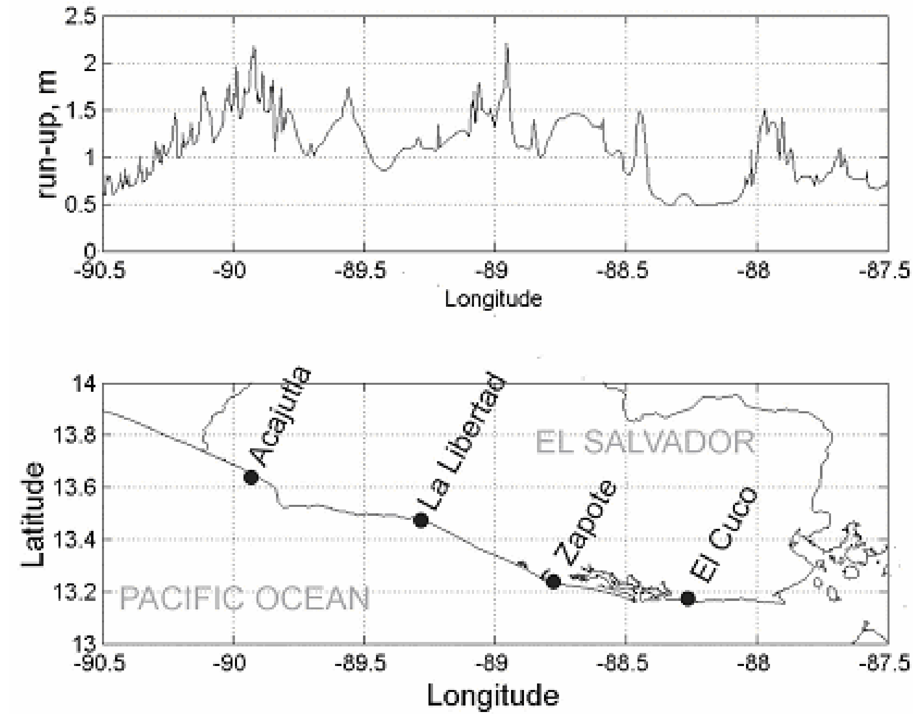


Figure 4.5: Run-up distribution generated by the 1906 Colombian tsunami along the Salvadorian coast.

(Fernandez, M., [2004])

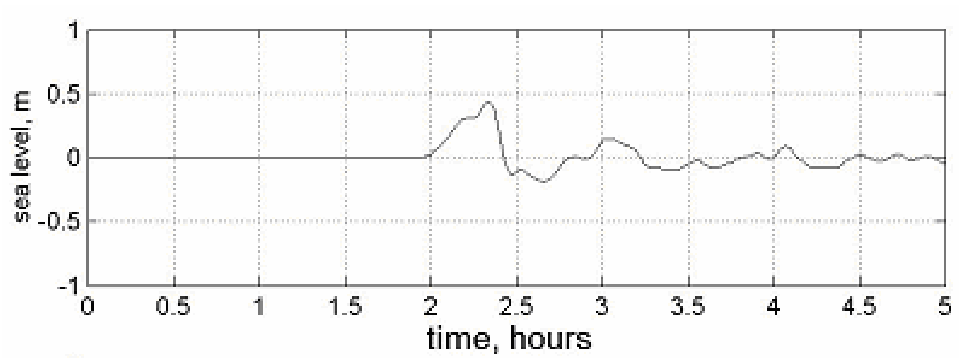


Figure 4.6: Tsunami signature generated by the 1906 Colombian tsunami at 3000-meter deep water offshore the Salvadorian coastline.

(Fernandez, M., [2004])

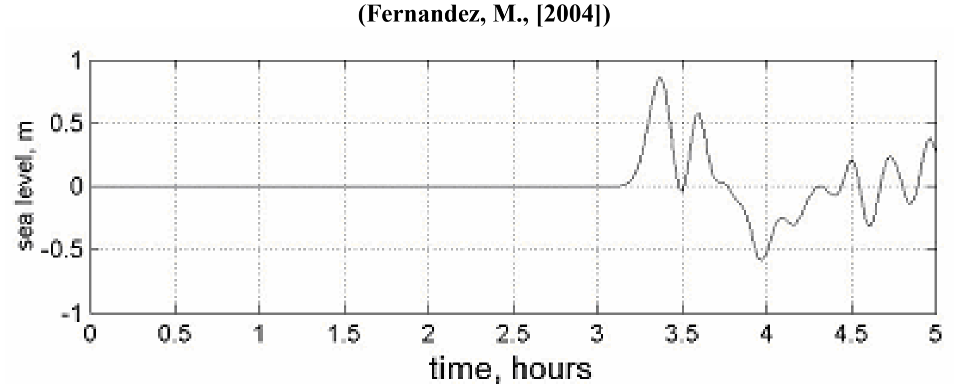


Figure 4.7: Tsunami signature generated by the 1906 Colombian tsunami at 50-meter deep water offshore the Salvadorian coastline.

(Fernandez, M., [2004])

Run-up heights at the Salvadorian coast varied between 0.5m and 2.2m. The northernmost coastal segment from the 89°W meridian presented higher values of vertical run-up compared with the southern coastal segment. According to the analysis, the highest run-up values would occur near Acajutla and La Libertad.

4.3.3 Location of areas affected by Tsunamis in El Salvador

Tsunami zonation is the designation of distinctive zones along coastal areas with varying degrees of tsunami hazard, risk or vulnerability for the purpose of disaster preparedness, planning, construction codes or public evacuation (UNESCO, IOC, [1991]). Such zonation scheme has not been implemented in Central America at the present time. However, studies that locate areas that were struck by historical tsunamis have been developed.

Locations affected by historical tsunamis occurred between 1539 and 1997 were presented by the project "Reduction of Natural Disasters in Central America, Earthquake Preparedness and Hazard Mitigation, phase II, 1996-2000" held by the Institute of Solid Earth Physics of the Bergen University, Norway (Molina, E., [1997]). The study revealed that 44 communities were struck at least once by tsunamis occurred at the Caribbean coast whereas 60 population centres were at the same situation at the Pacific coast (Fernández, M., et al [2000]).

At the Caribbean coast, historical tsunamis were located within two specific zones: the first one at the coastal segments that belong to Belize, Guatemala and Honduras and the second one at the coast of Costa Rica and Panama, Fig. 4.8 shows the tsunami wave fronts at the Caribbean Coast of Central America. Tsunamis waves at this coast have reached up to 5-meter height, and all together have killed 65 people (Fernández, M., et al, [2000]).

At the Pacific coast of Central America, tsunamis have occurred almost along the whole coast striking at least 60 population centres from which 11 are main ports with more than 1,000 inhabitants. It has been established that the number of communities affected by tsunamis reach 14 in Panama, 19 in Costa Rica, 9 in Nicaragua, 3 in Honduras, 6 in El Salvador and 8 in Guatemala. The places that have been affected fiercely are Golfito in Costa Rica, Acajutla in El Salvador, Pedasi in Panama and El Transito in Nicaragua. Figure 4.9 shows the tsunami wave fronts at the Pacific Coast of Central America Acajutla has been hit twice by destructive tsunamis. (Fernández, M., et al, [2000]).

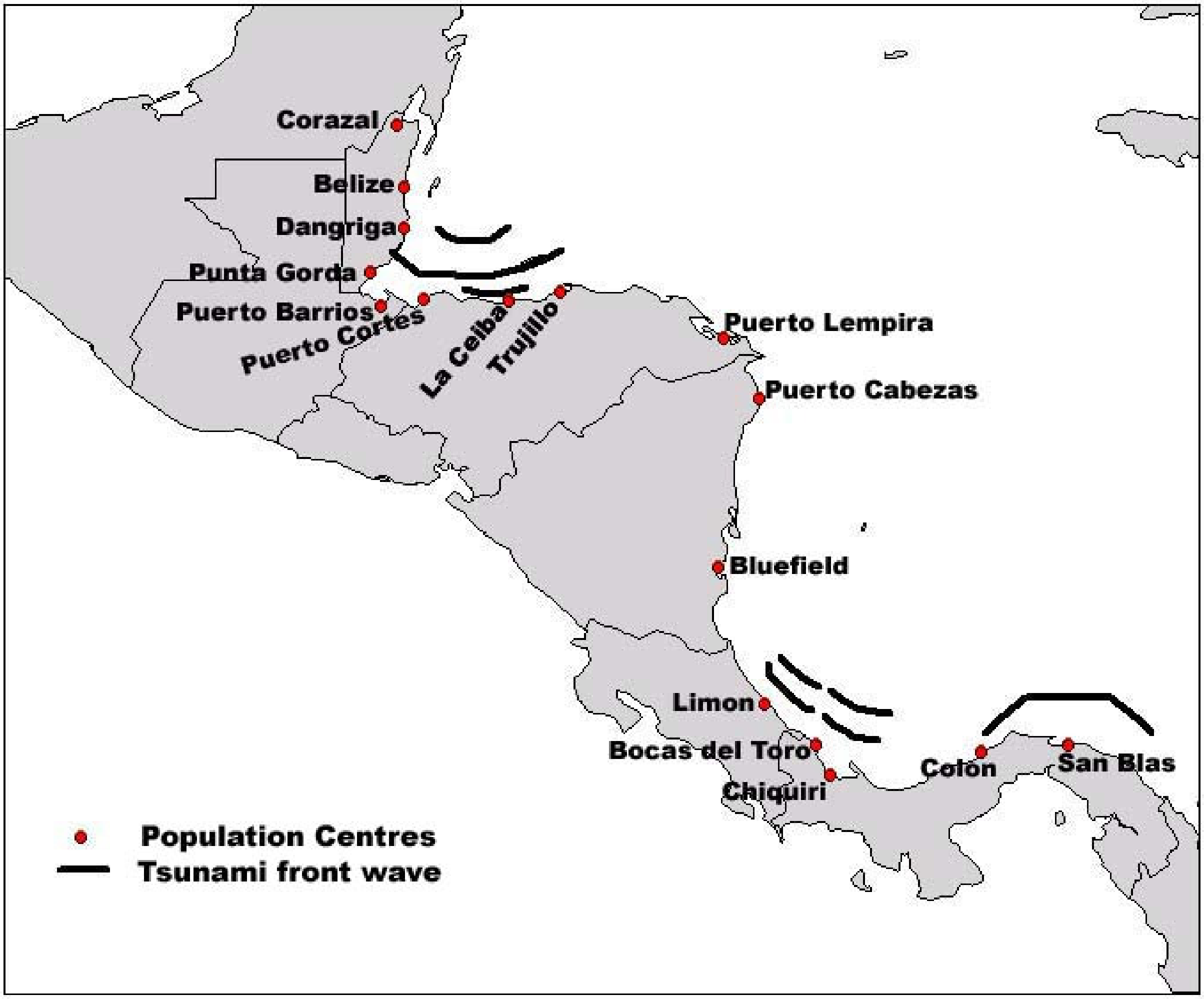


Figure 4.8: Historical tsunami location at the Caribbean coast of Central America between 1539 and 1996. (Fernandez, M. [2000])

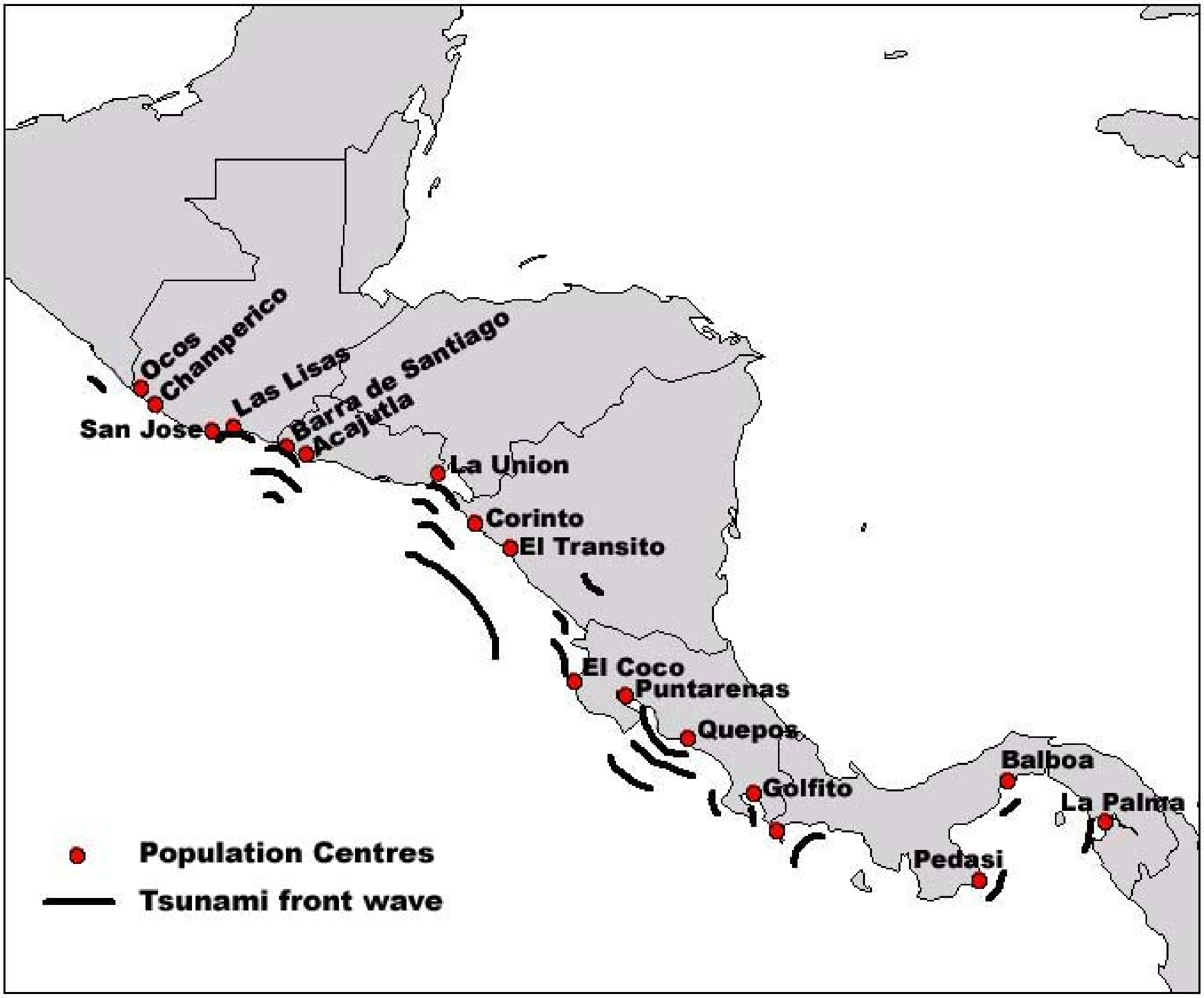


Figure 4.9: Historical tsunami location at the Pacific coast of Central America between 1539 and 1996. (Fernandez, M. [2000])

5. DATABASE USED FOR TSUNAMI HAZARD ASSESSMENT

5.1. INTRODUCTION

A database is a systematic, logical compilation of related or relevant information of a phenomenon (Harr, M. [1996]). In order to discriminate between database containing source information and purely tsunami parameters, two types of databases were introduced: the *tsunami event database* and the *tsunami run-up database*. Differences between these databases will be described in the sequel.

Tsunami event databases are more related to the tsunami magnitude, intensity, cause and source location whereas tsunami run-up databases describe run-up values and their measurement procedures at a specific location. Both databases contain run-up values and cause of the event, but they are presented in different ways.

A tsunami event database usually contains the information shown in Table 5.1, which is divided in three main groups: source, tsunami parameters and tsunami effects. Information required in each group will be described in sequel.

Tsunami source information includes date, location and association of the tsunami with earthquakes. Tsunami source date includes the date of the event and also includes the exact time when the tsunami was generated. Associated significant earthquake is a field that may vary until it is possible to assure that the tsunami was triggered by a seismic event. Source location is given in terms of country, city and geographical coordinates of the place where the tsunami started. If the source is an earthquake, its focal depth and magnitude are listed; the magnitude values can be expressed in surface, moment or body magnitude (M_s, M_w and m_b; respectively) [NOAA, www.ngdc.noaa.gov/seg/hazard/tsuintro.shtml].

Information related to tsunami parameters can be divided into cause, probability, tsunami magnitude, tsunami intensity, maximum run-up, number of run-ups and warning status. In the field called "*cause*" earthquakes, volcanic eruptions, landslides, meteorological phenomenon, explosion and combinations like earthquake-landslide, volcano-earthquakes or earthquake-volcano-landslide can be listed. The "*probability*" field defines if the credibility of the recorded tsunami classifying it as definite, probable, questionable or doubtful event. Abe or Iida magnitudes (M_t and m, respectively) are commonly used when defining tsunami magnitude. The Abe magnitude (See Eq 5.1) is related to the earthquake magnitude while the Iida magnitude (see Eq 5.2 and table 2.1) depends only on the tsunami run-up height. Tsunami intensity (I) is defined by Eq. 5.3 proposed by Soloviev and Go in 1974, and depends only on the tsunami run-up height. Maximum run-up height is the maximum wave vertical height registered (see Fig. 2.1); the number of run-ups observed is also included in the database. The area affected by the tsunami is considered in the warning status field, where it is defined if the event would affect distant, regional or local coasts. [NOAA, www.ngdc.noaa.gov/seg/hazard/tsuintro.shtml]. The following expressions are used to compute tsunami magnitude and intensity.

$$M_t = \log H + a \log R + D \quad (5.1)$$

$$m = \log_2 H \quad (5.2)$$

$$I = \log_2 (2^{1/2} H) \quad (5.3)$$

Tsunami effects such as deaths, injuries, destroyed houses and damage are also included in the database. These factors are quantified for each field and their cause is also defined. Comments on damage reports or on the accuracy of the information, references and pictures are commonly included in this kind of database.

Where H is the maximum run up height, a and D are constants[12] and R is the distance from the shoreline to the earthquake epicentre.

Table 5.1: Tsunami Event Database Information.

[NOAA, www.ngdc.noaa.gov/seg/hazard/tsuintro.shtml]

Tsunami Event Database
Tsunami source date
Year
Month
Day
Hour
Minute
Second
Associated significant earthquake
Tsunami source location
Country
City
Coordinates
Source Earthquake
Depth
Magnitude
Tsunami parameters
Cause
Probability
Magnitude
Tsunami intensity
Maximum run-up
Number of run-ups
Warning status
Tsunami effects
Deaths
Injuries
Destroyed Houses
Damage

Information contained in tsunami run-up databases can be divided in five main groups: tsunami source, run-up times, run-up location, run-up measurements and tsunami effects. Tsunami source

[12] These two constants take values around 1 and 5.8, repectively. (Indian Institute of Technology, Kapur [http://home.iitk.ac.in/student/balu/baba.ppt])

information includes the year, month and day when the tsunami was triggered, and the cause of the tsunami that is called associated tsunami event. Data included in the rest of the groups will be described below (NOAA, [www.ngdc.noaa.gov/seg/hazard/tsuintro.shtml]).

Arrival and *travel times* are included in the run-up time information. The first piece of information is generally expressed in days, hours and minutes whereas travel time is expressed only in hours and minutes. *Arrival time* is the time when the tsunami strikes the coast whereas travel time is the time that it takes to arrive from the source. Run-up location is described by the name of the country and city affected and by the geographical coordinates of the place.

Run-up measurement information is divided in four groups: type of measure, which specifies whether the run-up values were directly measured or if tidal gauges were used; run-up values, that specify the vertical and horizontal run-up values; period, which is typically the first cycle period expressed in minutes and finally first motion characteristics, that indicates if the tsunami started with a withdrawal or a rise of water at the coast.

Tsunami effects described in this kind of database have the same form of those included in tsunami event databases. They show number of deaths, injuries and damage to buildings. Comments, pictures and references are also included in this kind of database.

Table 5.2: Tsunami Run-up Database Information.

[NOAA, www.ngdc.noaa.gov/seg/hazard/tsuintro.shtml]

Tsunami Run-up Database		
Tsunami source date		
	Year	
	Month	
	Day	
Associated tsunami event		
Run-up times		
	Arrival time	
		Day
		Hour
		Minute
	Travel time	
		Hour
		Minute
Run-up locations		
	Country	
	City	
	Coordinates	
Run-up measurement		
	Height	
		Description
		Vertical
		Horizontal
	Period	
		First motion
Tsunami effects		
	Deaths	
	Injuries	
	Destroyed Houses	
	Damage	

Tsunami catalogues are more related to run-up databases in the sense that they describe the tsunami effects occurred at different locations. They are a compilation of tsunami magnitude and maximum height values registered or estimated at a specific location. These dataset are generally ordered by date. Generally speaking, catalogues also include the tsunami triggering mechanism, and sometimes a brief description of damage.

5.2. TSUNAMI CATALOGUE FOR EL SALVADOR

Tsunami catalogues started to emerge worldwide since 1947, before then, tsunamis were considered as secondary effects that accompanied earthquakes, volcanic eruptions or natural catastrophes. The first tsunami catalogues included parameters like observed run-up and tsunami intensities at the affected sites. Starting from the 1980's a description of tsunamigenic historical sources was included. Around 1990, reliability of the events was also introduced in the tsunami catalogues. Compiling tsunami catalogues is useful when computing the tsunamicity, tsunami hazard or tsunami risk of a specific region and also when defining the tsunamigenic sources and studying tsunami propagation (Tinti, S., et al., [2001]).

Efforts to specify the tsunamicity in Central America started after the devastating 1992 Nicaraguan tsunami. In 1997, a compilation of tsunamis occurred since the XVI century in the Pacific and the Caribbean coasts of Central America was presented[13]. Having found that 49 tsunamis occurred in that area, studies regarding to tsunami hazard mitigation and tsunami warning systems started to emerge.

The Central American tsunami catalogue was prepared as the second phase of the program called "Reduction of Natural Disasters in Central America" at the Institute of Solid Earth Physics at Bergen University. Forty-nine events occurred between 1539 and 1996 were gathered. That information includes source information (which is related to earthquakes in all of the cases), tsunami magnitude and its reliability, region affected, brief description of damage and sometimes figures that show the tsunami front waves.

A tsunami catalogue for El Salvador was included in 2004 in the series "Natural hazards in El Salvador" published by the Geological Society of America. Some of the events presented on it differ from those contained in the Central American tsunami catalogue due to underestimating of their maximum heights (Fernández, M., [written communication]). Both catalogues will be described below.

5.2.1 The Central America Tsunami Catalogue

The Central American tsunami catalogue was built in order to define the frequency, spatial distribution, characteristics and hazard of tsunamis in the region. The catalogue is a compilation of events that were mentioned in previous earthquake catalogues and/or tsunami catalogues and covers a spatial window that goes from 6° to 18° N and 93° to 77° W (Molina, E., [1997]).

As mentioned before, forty-nine tsunamis were recorded in Central America between 1539 and 1996. Earthquakes triggered almost all of those tsunamis except two of them that were supposed to

[13] The Central American Tsunami Catalogue was presented in 1997 as the second phase of the "Reduction of Natural Disasters in Central America" of the Institute of Solid Earth Physics of the University of Bergen, Norway and the Instituto de Sismología, Vulcanología, Hidrogeología y Meteorología de Guatemala (INSIVUMEH).

be s*eiches*[14] in the Nicaraguan lake and a tsunami caused by volcanic *lahars* at northern Nicaraguan coast.

Information gathered in the Central American tsunami catalogue was divided in three main time periods that correspond to the XVI-XVIII, the XIX and the XX centuries. Only 4 tsunamis were reported in the first period, whereas 11 and 35 events were reported in the XIX and XX centuries. Tsunami magnitudes varying between 0 and 2.5 (in the Inamura-Iida scale) were associated to these events and the damage reports described destruction of small ships, coastal infrastructure and sometimes destruction of small villages.

Datasets of each event include date, earthquake source parameters, tsunami parameters and tectonic region of the source. The date is related to the earthquake, rather than the *tsunami arrival time*. Earthquake source parameters included the latitude, longitude and magnitude (usually surface wave magnitude M_s). Tsunami source parameters specify the type of tsunami (local, regional or distant), the affected region and the tsunami magnitude under the Inamura-Iida scale. Information concerning to the tectonic region indicates the tectonic context of the event, for example if it was due to an earthquake belonging to the Cocos-Caribbean subduction zone, the boundary between the North American and the Caribbean plates, at the North Panama Deformed Belt or at the Panama Channel Discontinuity. Maps of the region struck by the tsunami and the triggering earthquake epicentres are commonly shown, and in some cases, figures regarding to macroseismicity are also included.

The list of tsunamis included in the Central American tsunami catalogue is shown in Appendix A, where specific events occurred in El Salvador are highlighted.

5.2.2 The Salvadorian Tsunami Catalogue

The Salvadorian tsunami catalogue was introduced in 2004[15]. It contains 11 datasets registered from 1859 to 1992 that were based basically on the Central American catalogue. Variation in magnitude can be noticed when both catalogues are compared, since re-assessment of vertical run-ups was performed.

Information regarding to each registered tsunami includes date, source parameters, tsunami location, tsunami magnitude and tectonic environment. The source parameters included are geographical coordinates, depth and surface wave magnitude (M_s) of the tsunamigenic earthquake. This information is presented in Table 5.3. Damage report and some remarks concerning to each event are also available, they are presented in Table 5.4.

All the tsunamis recorded in El Salvador were due to tsunamigenic earthquakes, 3 of them occurred at distant sources, 3 occurred at regional sources and the rest were triggered locally (See Figs. 3.7, 3.9 and 3.10). Tsunami magnitudes registered in the country vary between –2.5 and 4.0 in the Inamura-Iida scale. Distant tsunamigenic earthquakes had greater magnitudes than local tsunamigenic earthquakes. See Table 5.3.

[14] Seiche is the oscillation of water in enclosed lagoons or bays due to a disturbance (metereological conditions, earthquakes, etc.) that sets “waves” that are not tidal. The “wave” will bounce back and forth until its energy is dissipated through friction. (UNESCO, [1991]).

[15] The Salvadorian Tsunami Catalogue was introduced by the Central America Seismological Center (CASC), Centro de Investigación Científica y Educación Superior de Ensenada (CICESE) and Escuela Centroamericana de Geología, University of Costa Rica.

The westernmost and easternmost Salvadorian coastal segments (Acajutla and Golfo de Fonseca) are the locations that have been struck several times by tsunamis. Damage reports indicate that Acajutla has been strongly affected by tsunamis at least twice. See Fig. 5.1.

The number of deaths due to tsunamis in El Salvador has not been specified, but the Central America and the Salvadorian Tsunami catalogues estimate that locally triggered tsunamis have caused around 200 deaths (Fernández, et al, [2004] and Molina, E. [1997]). There are no reports regarding to economical damage, injuries or destruction caused by tsunamis.

5.3. RELIABILITY AND ACCURACY OF THE CATALOGUE

5.3.1 Overview

Once the tsunami catalogue information is obtained, it is important to establish the reliability and accuracy of such data. The term reliability may be defined as the probability that the expected value of a measurement determined with a certain technique is equal to the true value. Reliability may be affected by bias and systematic errors. Accuracy is also called precision and represents an estimate of the dispersion or scatter of the measurement around its expected value (Harr, M., [1987]).

Once earthquakes have been found to be the only cause of tsunamis, there are different aspects that should be considered to establish the reliability of the event: first if the occurrence of the earthquake and the tsunami was likely, second if the earthquake occurred but not the tsunami and third if the tsunami occurred but not the earthquake.

Accuracy depends more on the equipment used to measure the run-up values and the method to estimate the tsunami magnitude. The accuracy of the tsunami source parameters depends, in this case, on the procedure to locate the earthquake epicentre, and compute the seafloor deformation.

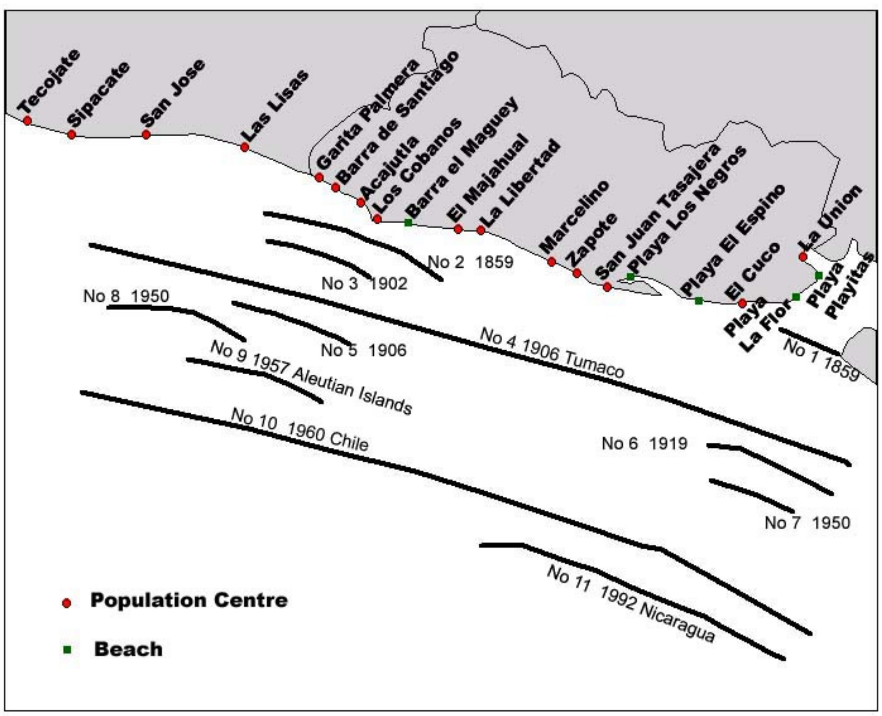


Figure 5.1: Tsunamis registered in El Salvador between 1539 and 1996.

(Fernández, et al, [2004])

Table 5.3 The Salvadorian Tsunami Catalogue.

(Fernández, et al, [2004])

			Earthquake Parameters					Tsunami Parameters			
No	Date	Time	Lat	Long		Ed	Em	Tsunami Location	Tm		Te
1	1859	0826	13	87.5	-	ND	6.2	Gulf of Fonseca	1.5	-	CO-CA
2	1859	1209	13.75	89.75	-	40	7	Acajutla	1.5	-	CO-CA
3	1902	0226	13	89.5	-	30	7	Garita Palmera	2	-	CO-CA
4	1906	0131	1	81.3	-	ND	8.1	The entire Coast	2	?	NA-SU
5	1906	0525	ND	ND	-	ND	ND	Los Negros Beach	-1	-	ND
6	1919	0629	13.5	87.5	>	40	6.7	Gulf of Fonseca	-1	-	CO-CA
7	1950	1005	10	85.7	<	60	7.7	The entire Coast	-1	-	CO-CA
8	1950	1023	14.3	91.8	-	S	7.3	Gulf of Fonseca	-1	-	CO-CA
9	1957	0310	51.63	171.4	-	ND	8.1	The entire Coast	3	-	PA-NO
10	1960	0522	38.2	73.5	-	32	8.5	The entire Coast	4	-	NA-SU
11	1992	0902	11.7	87.4	-	S	7.2	Gulf of Fonseca	-2.5	-	CO-CA

S	Shallow earthquake with macroseismic or instrumental evidence for a focus in the upper crust
No	Number of event
Elat	Earthquake latitude
Elong	Earthquake longitude
Ed	Earthquake depth
Em	Earthquake magnitude
Tm	Tsunami Magnitude (Inamura-Ida Tsunami Magnitude Scale, Molina, 1997)
Te	Tectonic enviroment
CO-CA	Cocos-Caribe margin
NA-SU	Nazca-South American Margin
PA-NO	Pacific-North American Margin
ND	No data

Table 5.4 Damage and remarks on tsunamis occurred in El Salvador.

(Fernández, et al, [2004])

No	Date	Time	Description
1	1859	0826	The tsunami generated by the earthquake caused severe damage to houses and boats. As a consequence of the furious waves, two vessels and a brigantine sank at La Unión, Gulf of Fonseca, El Salvador. In Addition, two canoes were damaged. Reports indicate that the situation in the sea was horrible.
2	1859	1209	This tsunami was accompanied by noise. The main observed effects in the water body were very agitated ocean in Acajutla, and high wave and recession of the water far from the shore, leaving fish floundered on the beach and terraces. Because of the recession, the docks and riverboat yards dried up almost to the breakwater. Standing out among the damage to structures is the destruction of the state warehouses and the flooding of the breakwater and the customhouse. The reports also say that caves and grottos collapsed.
3	1902	0226	There are similarities between this tsunami and that of 1859. First, both struck the western coast of El Salvador. Second, both were noisy tsunami; in this case, a loud rumble like cannon shots was heard. Finally, both experienced a falling of the water level, exposing the ocean bottom for a considerable distance. A large wave arose from the sea and reached the coast, causing damage to property and washing homes and trees out to the ocean. Three waves were observed. The magnitude of devastation from the tsunami was exceptional. The coast from Garita Palmera to Barra de Santiago and beyond (a distance about 120 km) was flooded. Barra de Santiango village was heavily damaged. The death toll was over 185 in the affected area.
4	1906	0131	Small tsunami waves were recorded throughout the Pacific Ocean. The tsunami was observed along the entire Pacific Coast of Central America.
5	1906	0525	High Waves invaded Los Negros Beach.
6	1919	0629	Flooded area in Gulf of Fonseca.
7	1950	1005	Small oscillations of the ocean level were recorded at La Unión, El Salvador, Iida, et al (1967) reported a wave of 8.9 meters high at La Libertad (El Salvador) but it is obviously a mistake.
8	1950	1023	A wave about 30 cm high was recorded at San Jose, Guatemala. A wave of 10 cm was also reported at La Unión.
9	1957	0310	This is a remote source tsunami. The associated earthquake was located at the Aleutian Islands Subduction Zone. A sea wave several meters high hit the Acajutla port and killed an undetermined number of coastal residents.
10	1960	0522	The tsunami from the great Chilean earthquake of 1960 (the largest seismic event in human history story). This tsunami affected the entire Pacific coast of Central America. It was recorded at La Unión (El Salvador) and San José (Guatemala) with heights of 0.5 m.
11	1992	0902	This is the largest known tsunami of Central America. In El Salvador, the effect was minimal.

There are some reports of waves reaching coastal houses after the 13 January 2001 earthquake in El Salvador, but no evidence was recorded. (Pullinger, C. [written communication]. Further research on this event was performed by the Tsunami Research Program, the Pacific Marine Environmental Laboratory and the National Oceanic and Atmospheric Administration (NOAA). The research consisted in modelling de possible tsunami triggered by the 13 January 2001 earthquake, two tsunami models having different seismic mechanisms (namely different values of strike, slip and dip) were run (http://www.pmel.noaa.gov/~koshi/elsalvador/). The water level values obtained at different coastal locations are shown in fig. 5.2. Higher water level values were computed at Punta San Juan, La Libertad and El Cuco (see fig. 3.9).

5.3.2 Reliability of the Central American Tsunami Catalogue

Information gathered in the Central America tsunami catalogue is a compilation of tsunami reports from different sources, in that sense, each event is characterised by a different level of reliability, which depends on the authors who compiled the database and on references used. (Molina, E., written communication, [2004]).

Textual descriptions from references were included in the Central American tsunami catalogue (no translations of the descriptions were made) in order to avoid the authors' interpretation of the events (Molina, E., [1997]).

According to the Central American tsunami catalogue, 36 out of 50 tsunamis are well documented and it is likely that 9 events did not occur. The reliability of each event is specified using question marks preceding or following the tsunami type symbol, as shown in table 5.5.

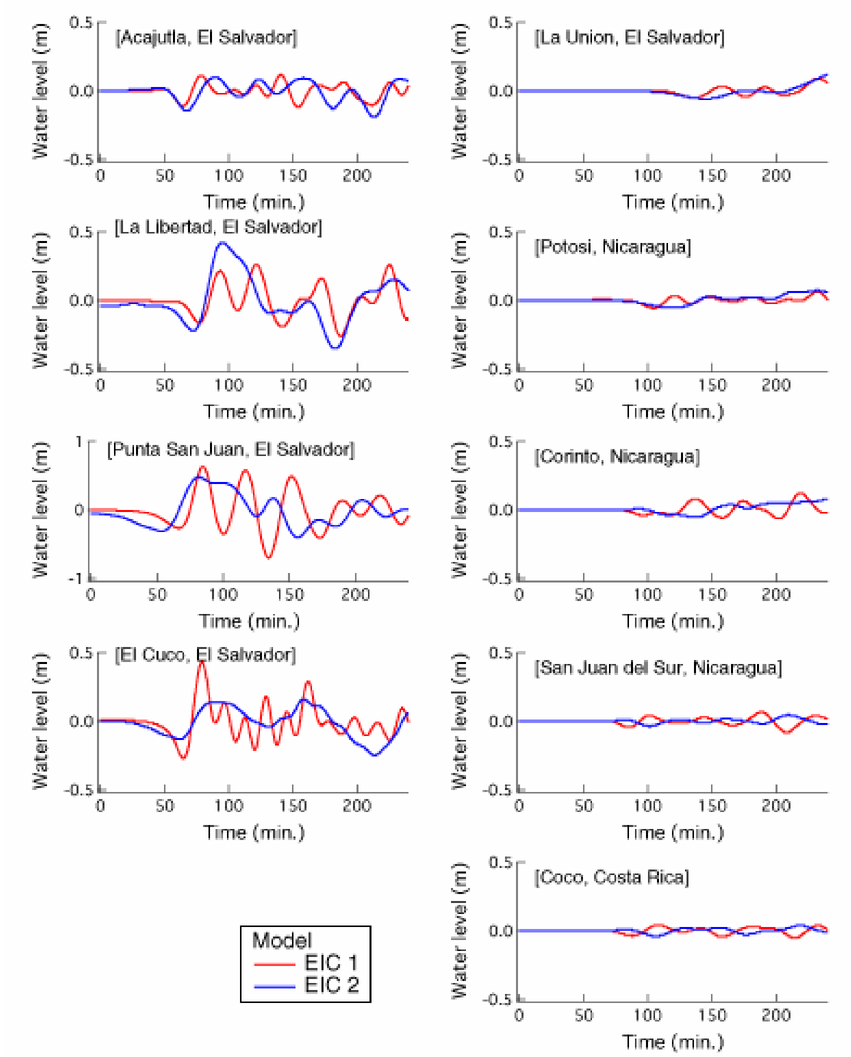


Figure 5.2 Water levels at different coastal locations after the 13 January 2001 earthquake in El Salvador. [http://www.pmel.noaa.gov/~koshi/elsalvador/]

Table 5.5 Data Reliability symbols in the Central America Tsunami Catalogue.

Symbol	Meaning
L?	Not reliable local tsunami, reliable earthquake occurrence.
?L	Not reliable earthquake, reliable tsunami phenomenon occurrence.
?L?	Both earthquake and tsunami occurrence are not reliable

5.3.3 Reliability of the Salvadorian Tsunami Catalogue

The Salvadorian Tsunami Catalogue is based on the Central American Tsunami Catalogue (Fernández M, [written communication]). Therefore, like the latter, provides different levels of reliability for the events. The vertical run-ups presented in the Salvadorian Tsunami Catalogue were estimated based on historical reports that described the probable height of the waves and these heights were scaled under the Inamura-Iida scale (see Table 2.1). The former catalogue includes a new source that describes the 1902 tsunami (see Tables 5.2 and 5.3) according to a survivor (Fernández, M. [written communication]).

The main problem that the authors[15] of the Salvadorian Catalogue faced was the fact that in some cases, seismic information was registered as it had occurred several days after the seismic event. This leads to confusion or contradiction in data when consulting sources of information (Fernández, M. [written communication]).

5.4. COMPLETENESS OF THE CATALOGUE

Some of the natural disasters such as earthquakes, landslides and tsunamis that occurred in ancient times are likely to have not been registered due to a) the lack of measuring equipment, b) they passed unnoticed, especially weak events or c) they occurred in inhabited places. This explains the reduced number of events registered in the catalogues and their increase in more recent times. In order to account for this fact, the concept of *completeness* has started to emerge to event catalogues not only for earthquakes but also for tsunamis. A catalogue can be considered complete if it contains a more or less constant number of events registered along constant time intervals (Albarello, D. et al [2001]).

Completeness can be estimated using a graphical method called "visual cumulative method to estimate completeness". The method is originally applied to seismic catalogues to find their *periods of completeness* (Albarello, D. et al [2001]). Having chosen a seismic catalogue of a region, the steps to evaluate its completeness under this method are:

a) Select the homogenising criteria that will be adopted for the analysis (generally magnitude or intensity).
b) Divide the selected criteria in different interval classes. For example, If magnitude is the selected criteria, the smallest magnitude registered is 3 and the greatest is 6; a possible arrange of interval classes could be [0,3], [0,4], [0,5] and [0,6] in each class would be included the events whose magnitude is smaller or equal to the upper bound limit of the interval class. Each class interval will be analysed separately.
c) Choose a time interval for the analysis (20 years is commonly used).
d) For each time interval and for each interval class criteria (magnitude) count the number of events that exceed the upper boundary of the interval class considered.
e) Plot the number of events computed in (d) for each time interval.
f) Time intervals that fit a trend defined by a straight line would be considered complete
g) If the trend found can be attributed to a few decades, the catalogue is considered complete.

The visual cumulative method to estimate completeness has been applied to seismic catalogues in recent years. In this thesis, since all the events contained in the Salvadorian Tsunami Catalogue were triggered by major earthquakes, the method will be implemented to estimate the completeness of the catalogue. Distant tsunami magnitude values recorded in the catalogue (events 4, 9 and 10 shown in table 5.3) are near source magnitude values (Férnandez, M. [written communication]), damage description of these events were used to assign magnitude values that are according to run-up values recorded. These magnitude values are –0.5, 2 and –0.5 for events 4, 9 and 10 shown in table 5.3.

The results of the visual cumulative analysis performed in order to establish the completeness of the Salvadorian tsunami catalogue are shown in Table 5.6. The time interval chosen was 20 years, starting from 1840. Threshold magnitude values chosen were –2.5, -1.0 and 2.0. Results obtained are shown in the figures below.

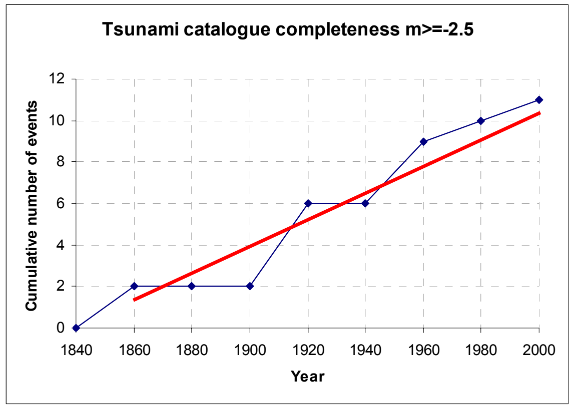


Figure 5.3: Completeness of the Salvadorian Tsunami Catalogue m>=-2.5

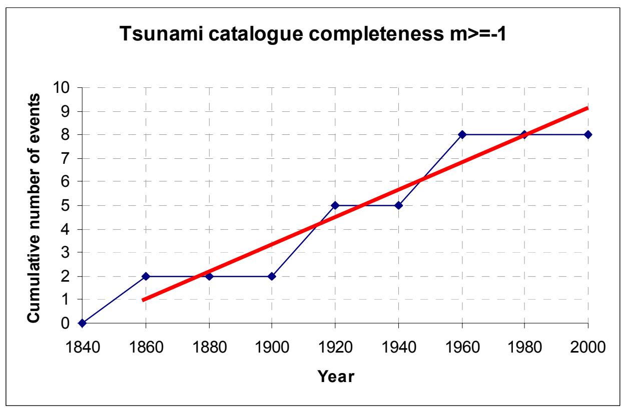


Figure 5.4: Completeness of the Salvadorian Tsunami Catalogue m>=-1.0

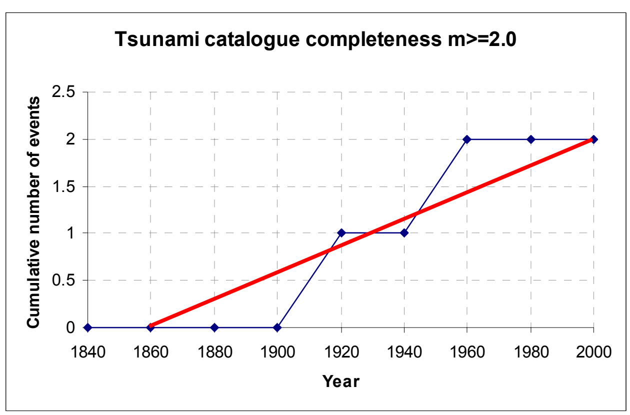


Figure 5.5: Completeness of the Salvadorian Tsunami Catalogue m>=2.0

From the completeness analysis performed it can be said that the Salvadorian tsunami catalogue can be considered complete from 1859. Table 5.6 presents a summary on the completeness of the Salvadorian Tsunami Catalogue. Being conservative, the completeness period of the Salvadorian tsunami catalogue can be estimated as 100 years as shown in figure 5.6. The non-conservative completeness period will be used when performing the probabilistic tsunami hazard assessment of El Salvador (see chapter 6).

Table 5.6 Completeness of the Salvadorian Tsunami Catalogue.

Tsunami magnitude (Tm)	Class	Completeness Period
-2.5	I	1859-2000
-1	II	1859-2000
2	III	1859-2000

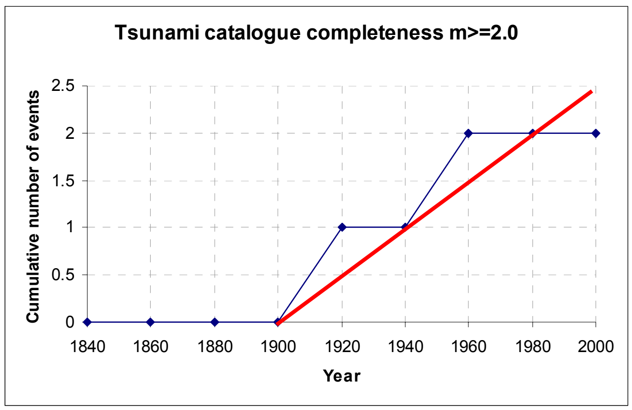


Figure 5.6: Conservative estimation of the Salvadorian Tsunami Catalogue m>=2.0

6. PROBABILISTIC TSUNAMI HAZARD ASSESSMENT

6.1. OVERVIEW

Tsunami hazard can be estimated based on historical data, in particular on maximum vertical run-up registered or recorded in a specific region. Information regarding location and maximum vertical run-up will be here in after called historical data or tsunami data set. The accuracy of the tsunami hazard estimation depends on both reliability and amount of information gathered. It can be stated that five tsunami data sets would be enough to have an acceptable approach of a region's hazard, the accuracy of the results will increase with the number of reliable tsunami data sets available (Kaistrenko and Pinegina, [2001]).

Assessing a probabilistic tsunami hazard in a region includes first gathering sufficient historical information, second finding a recurrence function that describes the frequency of tsunamis in the area and third based on the recurrence function estimate the maximum run-up tsunami that is expected to occur in the region for a given return period.

6.2. PROBABILITY MODEL FOR TSUNAMI HAZARD ASSESSMENT

Having obtained the tsunami catalogue for El Salvador (see chapter 5), the second step when performing the probabilistic tsunami hazard assessment of the country is finding the frequency function that describes the tsunami occurrence in the area.

The frequency function or recurrence function is a mathematical law that describes the frequency of occurrence of a tsunami by vertical run-up values. Generally speaking, tsunamis whose vertical run-ups are small are more frequent than those whose vertical run-ups reach several meters. Power law[16], upper-truncated power law[17] and negative exponential[18] functions are usually used to as function shapes that describe tsunami frequency laws. (Burroughs, S. and Tebbens, S., [2005]). The frequency law that fits better the tsunami data set registered in a region should be used to estimate the maximum vertical run-up that expected to occur for a given return period.

---

[16] Negative power law is described by $\phi(h) = C * h^{-b}$ where $\phi(h)$ is the frequency function, h is tsunami vertical run-up, C is a constant that describes the tsunami activity level of the region and b is the constant exponential value of the function.

[17] Negative upper tuncated power laws have the form $\phi(h) = C(h^{-b} - h_o^{-b})$ where $\phi(h)$ is the frequency function, h is tsunami vertical run-up, h_o is a threshold run-up value associated to frequency of occurrence equal to cero, C is a constant that describes the tsunami activity level of the region and b is the constant exponential value of the function.

[18] Negative exponential functions are described by $\phi(h) = C * e^{-h*b}$ where $\phi(h)$ is the frequency function, h is tsunami vertical run-up, C is a constant that describes the tsunami activity level of the region and b is the constant exponential value of the function.

The probabilistic model to be implemented in this study was proposed by Kaistrenko and Pinegina in their analysis for the Zhupanovo, Kamchacka region, in Russia (Kaistrenko and Pinegina, [2001]). This approach aims to compute the probability of occurrence of a tsunami whose maximum vertical run-up exceeds a threshold value. The probability that "n" tsunamis exceed the maximum height threshold value is computed by Eq. 6.1, where $\phi_{(h_0)}$ is the tsunami recurrence function, which according to this model, is a negative exponential function, T is the time observing interval and h_0 is the vertical run-up threshold value chosen.

$$P_n(h \geq h_o) = \frac{\left[\phi_{(h_o)} \cdot T\right]^n}{n!} \cdot e^{-\phi(h_o) \cdot T} \qquad (6.1)$$

The model is applied under the assumption that frequency of major earthquakes fit well in a Poissonian law scheme whereas aftershocks or foreshocks deviate from it. Since tsunamis are caused mainly by large earthquakes, it is likely that frequency of tsunamis also fit well the Poissonian law scheme (Kaistrenko and Pinegina, [2001]).

Under this model assumptions, the tsunami recurrence function is a regional characteristic that depends on the rate of occurrence of historical tsunami data and can be computed by Eq. 6.2. The negative exponential form reflects the fact that extremely large tsunami vertical run-ups are not very frequent. Parameters involved in this function depend on regional tsunami observations; $H^*(x)$ and f(x) are called calibrated or characteristic tsunami height and frequency at the "x" point, respectively. Tsunami frequency, f(x), is a regional parameter that can be considered constant for the same geographical region.

$$\phi(h) = f(x) \cdot e^{\frac{-h}{H^*(x)}} \qquad (6.2)$$

Once $H^*(x)$ and f(x) have been computed, the expected tsunami height at a specific return period "T" (expressed in years) can be computed by:

$$h_T = H^*(x) \cdot \ln(T \cdot f(x)) \qquad (6.3)$$

The methodology followed to implement this approach to assessing the probabilistic tsunami hazard in El Salvador is described in Section 6.3.

6.3. METHODOLOGY USED FOR TSUNAMI RUN-UP PREDICTIONS AND HAZARD SCENARIOS ASSESSMENT

Based on the magnitude and damage description of the events gathered in the Salvadorian tsunami catalogue, probable maximum and minimum run-up values were estimated for the locations chosen as hazard scenario (see section 6.3.1). The procedure is described in more details below.

6.3.1 Hazard scenarios

Hazard scenarios are spatial locations that have been selected for assessing the potential hazard towards a specific phenomenon. Tsunami hazard scenarios are usually locations that have been struck by these events once or several times throughout history.

Considering the tsunamigenic historical information in El Salvador, it can be said that the country has been mainly hit by tsunamis at its westernmost and easternmost coast, in particular at Acajutla and La Unión. These places will be considered the principal tsunami hazard scenarios of El Salvador. See Figs. 6.1 and 5.1.

According to Kaistrenko and Pinegina, [2001] , tsunami frequency values (f(x)) vary very slowly within closely spaced locations; therefore frequency values can be considered the same for those events occurred within 100 km far from Acajutla or La Unión and they will be included in the tsunami history of these places. Following this, 7 and 6 events contained in the Salvadorian Catalogue were attached to Acajutla and La Unión, respectively.

Figure 6.1 Map of El Salvador.

6.3.2 Run-Up Estimation

The magnitudes of the events included in the Salvadorian tsunami catalogue were estimated under the Inamura-Iida scale and therefore they vary between the maximum and minimum run-ups presented in Table 6.1. The magnitude values that do not appear in the table were interpolated except in the case concerning to event number 11 (see Table 6.2). For that particular case the run-up was estimated using the relation $m = \log_2 H$ because interpolation was not valid since the event magnitude was out of the range of data presented in Table 6.1.

Table 6.1 Tsunami Magnitude Scale Inamura-Iida

(Molina, [1997])

m	Hmax	Hmin	Damage
4	30	30	Considerable damage along more than 500 km of coast line
3	20	10	Considerable damage along more than 400 km of coast line
2	6	4	Damage and lives lost in certain landward areas
1	2	2	Coastal and ship damage
0	1	1	Very small damage
-1	0.5	0.5	None

Magnitudes of distant events registered in the Salvadorian tsunami catalogue (tsunamis 4, 9 and 10 presented in Table 6.2) are near-source magnitudes and therefore the vertical run-up values computed using them are related to near-source coasts and would not be realistic values for the locations along the Salvadorian coast. Probable maximum and minimum vertical run-ups of these events were estimated based on the Modified Sieberg Sea-wave Intensity Scale (see appendix B) and damage descriptions presented in Table 5.4. Once the intensity (I) of the events were estimated, their run-up values (h) were computed by the Soloviev and Go (1974) relation:

$$I = \log_2(2^{1/2} * h) \tag{6.4}$$

The probable minimum, maximum and average tsunami run-ups associated to the events occurred in El Salvador are shown in Table 6.2. These values will be used in the probabilistic tsunami hazard assessment performed in this study.

Table 6.2 Vertical run-up height estimation based on the Salvadorian Tsunami Catalogue.

No	Date	Time	Tsunami Location	Tm		H ave	H max	H min
1	1859	0826	Gulf of Fonseca	1.5		2.8	3.50	2.50
2	1859	1209	Acajutla	1.5		2.8	3.50	2.50
3	1902	0226	Garita Palmera	2		4.0	4.50	3.50
4	1906	0131	The entire Coast	2	?	0.75	1.00	0.50
5	1906		Los Negros Beach	-1		0.5	0.75	0.25
6	1919	0629	Gulf of Fonseca	-1		0.5	0.75	0.25
7	1950	1005	The entire Coast	-1		0.5	0.75	0.25
8	1950	1023	Gulf of Fonseca	-1		0.5	0.75	0.25
9	1957	0310	The entire Coast	3		9.0	10.00	8.00
10	1960	0522	The entire Coast	4		0.75	1.00	0.50
11	1992	0901	Gulf of Fonseca	-2.5		0.18	0.20	0.15

Once the average tsunami run-up values were computed, they have to be associated to the locations that have been identified as hazard scenarios. Tsunamis that have occurred at Acajutla or near its vicinity (at about 100 km far from Acajutla) are shown in Table 6.3, and those occurred at La Unión or nearby (at about 100 km far from La Union) are shown in Table 6.4. Spatial location of those events can be seen in Fig. 5.1.

According to the probabilistic model adopted in this study, the tsunami frequency function should be computed to estimate maximum run-ups that would be expected for different return periods. The frequency function shape selected for this particular case is the negative exponential law since is the shape that fits the most the analysis database. Based on average vertical run-ups and the cumulative number of events that exceed that vertical run-up, a frequency function will be found for each hazard scenario. The methodology for computing the frequency function is explained below.

Table 6.3 Estimated Vertical Run-Up Values at Acajutla.

No	Date	Time	Tsunami Location	Tsunami Magnitude (Tm)		H (m)	H max (m)	H min (m)
2	1859	1209	Acajutla	1.5		2.8	3.50	2.50
3	1902	0226	Garita Palmera	2		4.0	4.50	3.50
4	1906	0131	The entire Coast	2	?	0.75	1.00	0.50
5	1906		Los Negros Beach	-1		0.5	0.75	0.25
8	1950	1023	Gulf of Fonseca	-1		0.5	0.75	0.25
9	1957	0310	The entire Coast	3		9.0	10.00	8.00
10	1960	0522	The entire Coast	4		0.75	1.00	0.50

Table 6.4 Estimated Vertical Run-Up Values at La Unión.

No	Date	Time	Tsunami Location	Tsunami Magnitude (Tm)	H (m)	H max (m)	H min (m)
1	1859	0826	Gulf of Fonseca	1.5	2.8	3.50	2.50
4	1906	0131	The entire Coast	2 ?	0.75	1.00	0.50
6	1919	0629	Gulf of Fonseca	-1	0.5	0.75	0.25
7	1950	1005	The entire Coast	-1	0.5	0.75	0.25
10	1960	0522	The entire Coast	4	0.75	1.00	0.50
11	1992	0901	Gulf of Fonseca	-2.5	0.18	0.20	0.15

The values considered in the analysis are the run-up values and the natural logarithm of the cumulative frequency normalised with respect to the time observing interval. In order to find the tsunami recurrence function at each hazard scenario, linear regression[19] of experimental data was performed. Weighted least square was chosen as the most appropriate method to perform the linear regression because it attributes different levels of reliability to each dataset (see Appendix C).

The tsunami recurrence function will take a negative exponential form and its characteristic height and tsunami frequency of each hazard scenario will be computed using a Matlab computer code. The code computes the slope and intercept of the linear regression and the parameters of the recurrence function and it is shown in Appendix D. The input values used for the code are shown in table 6.5 under the columns "x" and " lnN' ", the latter will be taken as "y".

Table 6.5. Input Data for computing the Tsunami Recurrence Function of Acajutla and La Unión.

ACAJUTLA

x	n	N	ln N	N'	ln N'	1/N'	var
0.5	2	7	1.94591015	0.04964539	-3.0028497	20.14	0.00260
0.75	2	5	1.60943791	0.03546099	-3.339322	28.20	0.00313
3	1	3	1.09861229	0.0212766	-3.8501476	47.00	0.00998
4	1	2	0.69314718	0.0141844	-4.2556127	70.50	0.01426
9	1	1	0	0.0070922	-4.9487599	141	0.04714

LA UNION

x	n	N	ln N	N'	ln N'	1/N'	Var
0.175	1	6	1.7917595	0.0425532	-3.1570004	23.50	0.15615
0.5	2	5	1.6094379	0.035461	-3.339322	28.20	0.20064
0.75	2	3	1.0986123	0.0212766	-3.8501476	47.00	0.23864
3	1	1	0	0.0070922	-4.9487599	141	0.72896

x	Vertical run-up values (m)
n	Frequency of vertical run-up values
N	Cumulative number of events with vertical run-upt greater or equal to h_i
lnN	Natural logarithm of N
N'	Cumulative frequency normalised with the time observing interval (1/years)
lnN'	Natural logarithm of N'
1/N'	Recurrence interval (years)
var	Variance of the vertical run-up values

[19] Linear regression is performed in order to compute the slope and intercept of the straight line defined by the run-up value (x) and the natural logarithm of their cumulative frequency (ln N'). These values will be used to express the recurrence function in its exponential form.

6.3.2.1 Tsunami recurrence function at the hazard scenarios.

Parameters of the regression found for Acajutla are shown in Table 6.6. The relation that these datasets follow is $\ln N' = -3.011 - 0.2608(h)$. The standard deviation was 0.288. The characteristic height and frequency at Acajutla resulted to be 3.83 m and 0.0492, respectively. Then the tsunami recurrence function is described by the function $\phi(h) = 0.0492 \cdot e^{\frac{-h}{3.83}}$, where h shall be expressed in meters. Figures 6.2 and 6.3 show the linear regression and the tsunami recurrence function attributed to this hazards scenario.

Table 6.6 Parameters of the regression and recurrence function parameters for Acajutla

ACAJUTLA		
Linear Regression		
Intercept	-3.011	
Slope	-0.2608	
SD	0.288	
Recurrence Function		
$H^*_{(x)}$	3.83	m
$F_{(x)}$	0.0492	

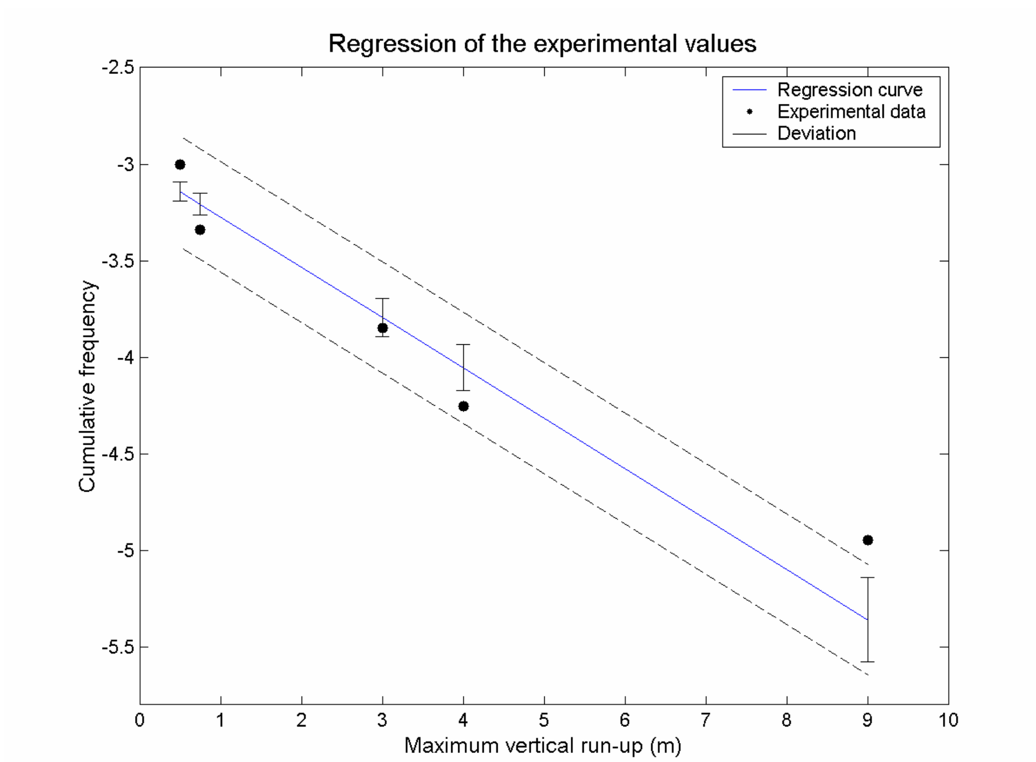


Figure 6.2: Linear regression, tsunami recurrence function at Acajutla.

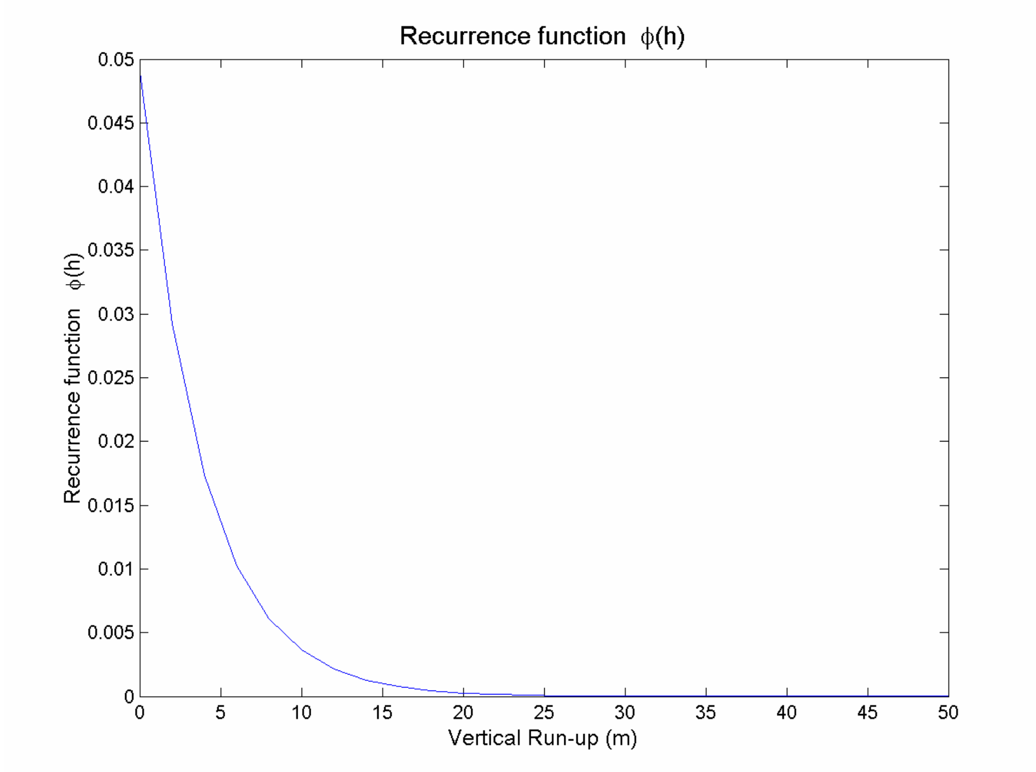


Figure 6.3: Tsunami recurrence function at Acajutla.

Parameters of the regression found for La Unión are shown in Table 6.7. The relation that these datasets follow is $\ln N' = -3.1086 - 0.6524(h)$. The standard deviation was 0.213. The characteristic height and frequency at La Unión resulted to be 1.53 m and 0.0447, respectively. Then the tsunami recurrence function is described by the function $\phi(h) = 0.0447 \cdot e^{\frac{-h}{1.53}}$, where h shall be expressed in meters. Figures 6.4 and 6.5 show the linear regression and the tsunami recurrence function attributed to this hazards scenario.

Table 6.6 Parameters of the regression and recurrence function parameters for La Unión

LA UNION		
Linear Regression		
Intercept	-3.109	
Slope	-0.6524	
SD	0.213	
Recurrence Function		
$H^*_{(x)}$	1.53	m
$f_{(x)}$	0.0447	

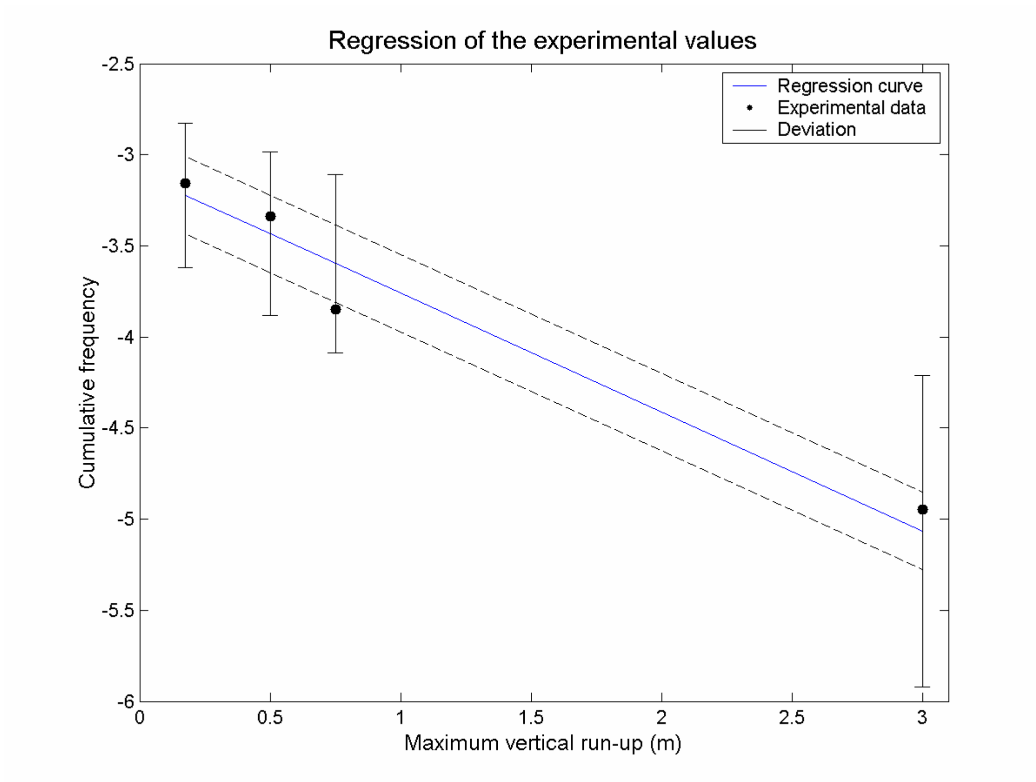


Figure 6.4: Linear regression, tsunami recurrence function at La Unión.

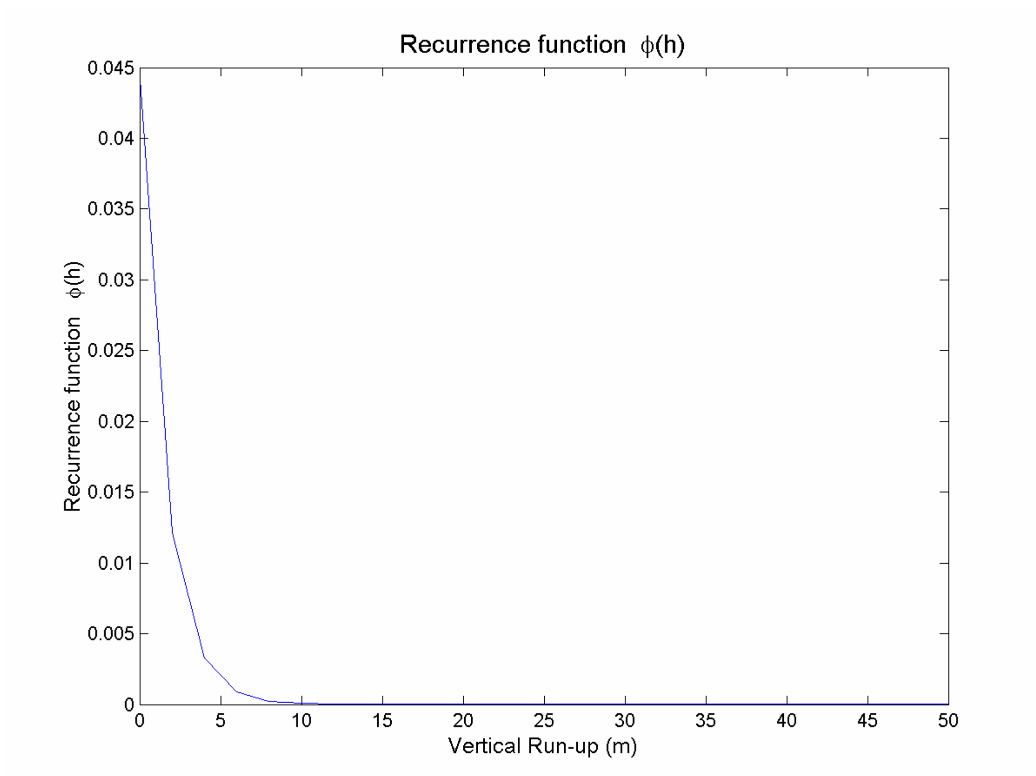


Figure 6.5: Tsunami recurrence function at La Union.

6.3.2.2 Expected tsunami heights at the hazard scenarios

Using Equation 6.3, expected heights corresponding to different return periods can be obtained once the tsunami recurrence function is computed. Expected heights for return periods of 250 and 475 years were calculated for both hazard scenarios. These values are shown in table 6.8.

Table 6.8: Expected tsunami heights values for T=250 and 475 years.

ACAJUTLA		LA UNION	
T (years)	h_T (m)	T (years)	h_T (m)
250	9.62	250	3.70
475	12.08	475	4.68

6.3.2.3 Logic tree approach for the tsunami hazard assessment of El Salvador

The logic tree approach is a methodology designed to deal with uncertainty of probabilistic models. This method allows weighting results of different models through the establishment of a weighting factor, which reflects the likelihood that the model applied is correct. The tree approach consists of a group of nodes and branches that represent different models followed in the analysis (Kramer, S., [1996]).

The logic tree approach was used in order to establish the sensitivity to the completeness of the probabilistic model followed to assess the tsunami hazard of El Salvador. Completeness periods (ΔT) computed from the catalogue and conservatively estimated in the completeness analysis performed in section 5.3 were input into the probabilistic model adopted in this study. For these periods, events with run-up exceeding the threshold value were selected to apply the probabilistic model proposed by Kastreinko and Piregnina (2001) in order to obtain expected run-up values. Parameters of each recurrence function and expected run-up values are shown in table 6.9.

Table 6.9: Variation of tsunami recurrence function and expected run-up values with return period.

	H>= (m)	ΔT (years)	H*(x) (m)	f(x)	SD	Expected Height $h_{T=250}$ (m)	$h_{T=475}$ (m)	
A1	0.5	141	3.8337	0.0492	0.2879	9.62	12.08	Acajutla
A2	0.5	100	3.8337	0.0694	0.2879	10.94	13.40	Acajutla
L1	0.2	141	1.5328	0.0447	0.2130	3.70	4.68	La Union
L2	0.2	100	1.5364	0.06290	0.2133	4.23	5.22	La Union

Figures 6.6 and 6.7 show the results from the logic tree approach at Acajutla and La Unión. The nodes selected for the approach are time interval and run-up values. Branches at the first node are completeness periods from the catalogue and from the conservative completeness analysis. At the second node, branches indicate the probabilistic model. Weighting factors chosen for each branch are shown in Figs. 6.6 and 6.7, higher weighting factors were given to the completeness period computed from the catalogue.

Generally speaking, expected run-up values decreased with the completeness period, and so did recurrence functions. Values of expected run-up are shown in table 6.9 and Figs. 6.6 and 6.7. Recurrence functions for each case are shown in Figs. 6.8 and 6.9. The relative likelihood of each result can be computed by multiplying all of the weighting factors preceeding the node of interest, the likelihood values obtained for this analysis are shown at the end of the branches in Figs. 6.6 and 6.7.

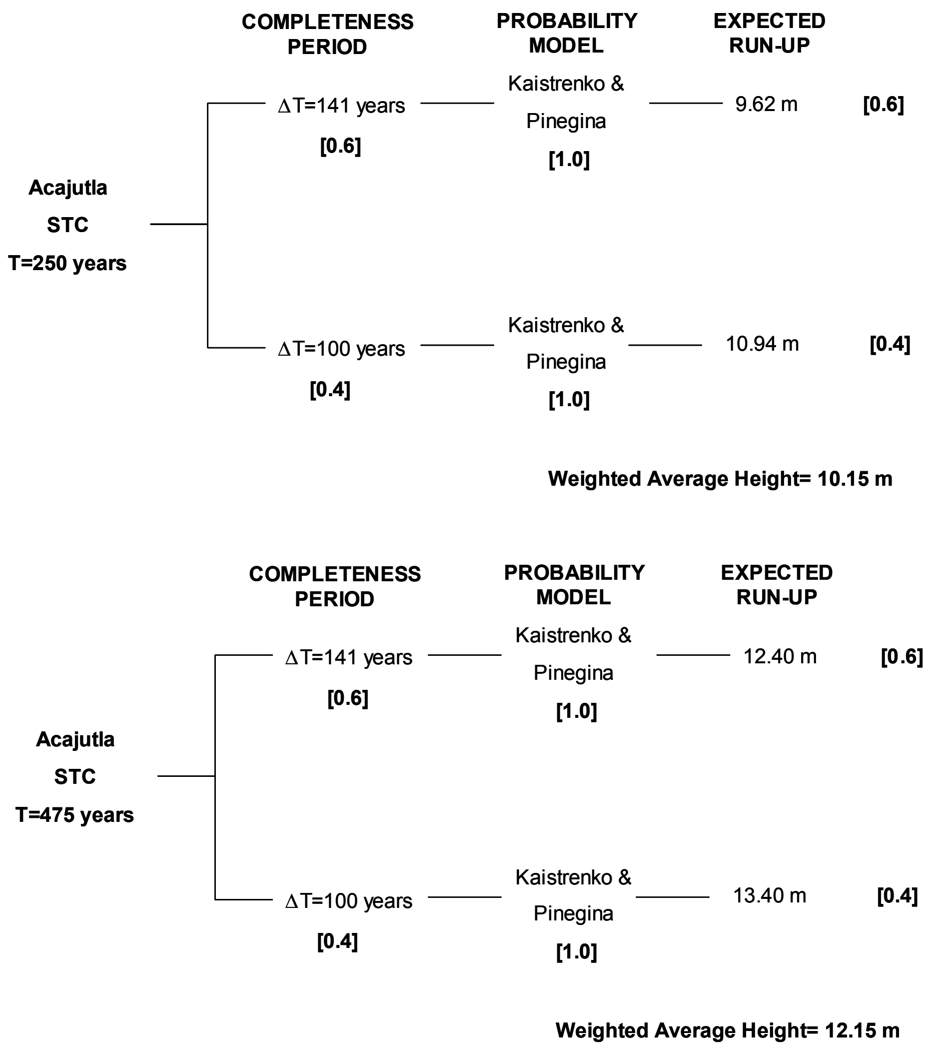


Figure 6.6: Logic tree approach at Acajutla.

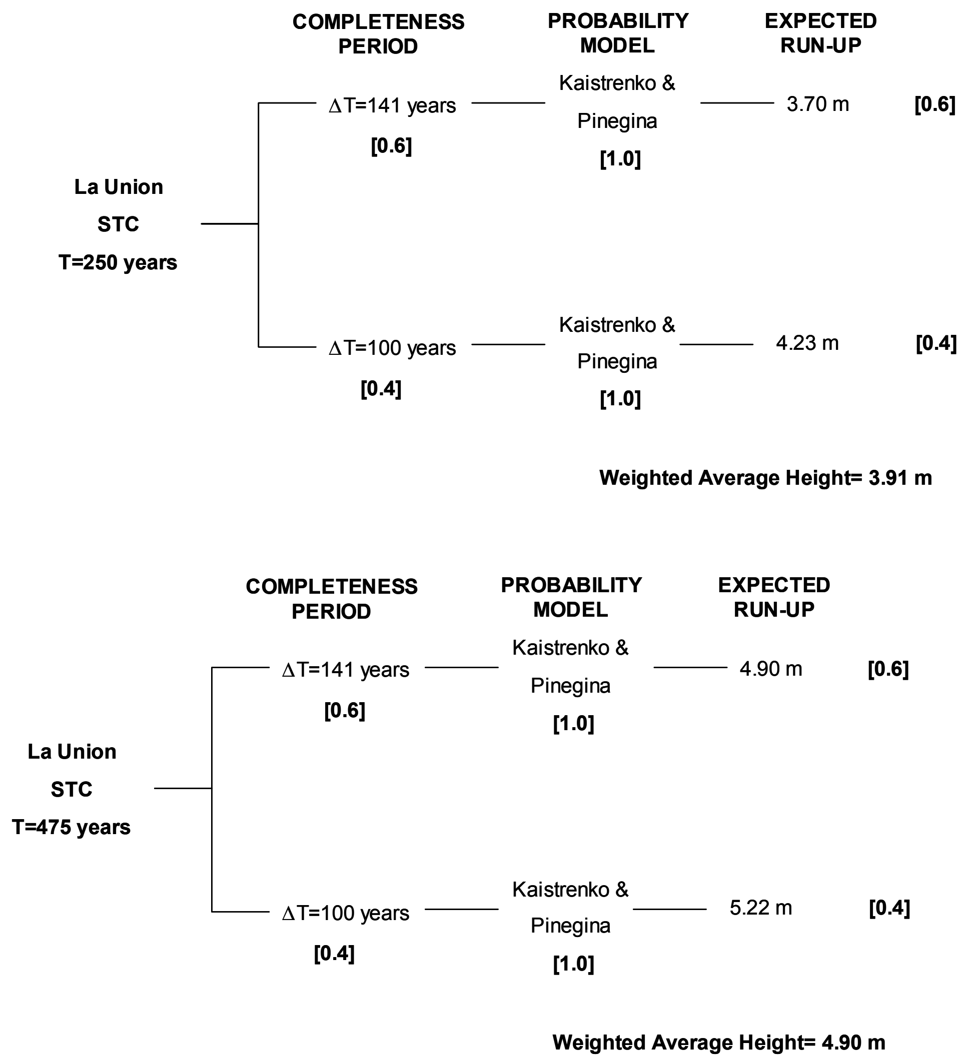


Figure 6.7: Logic tree approach at La Unión.

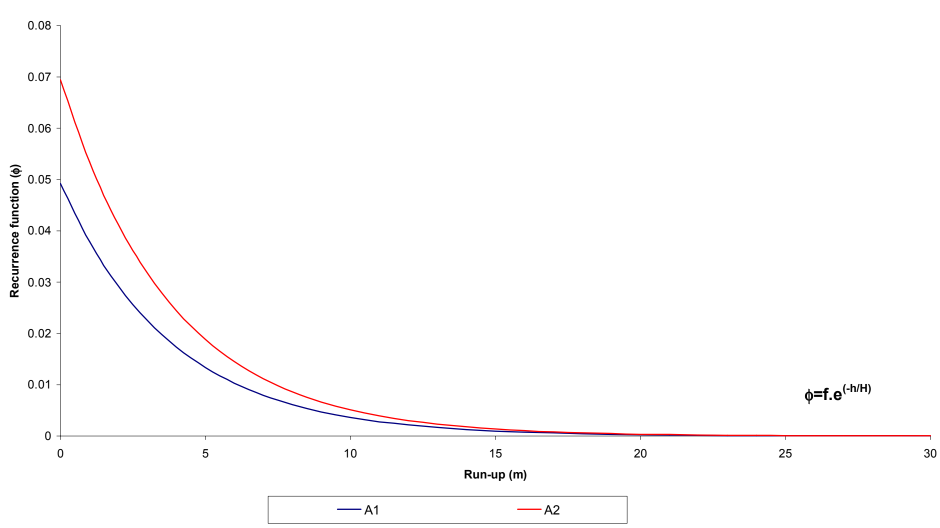


Figure 6.8: Variation of the recurrence function with return period at Acajutla.

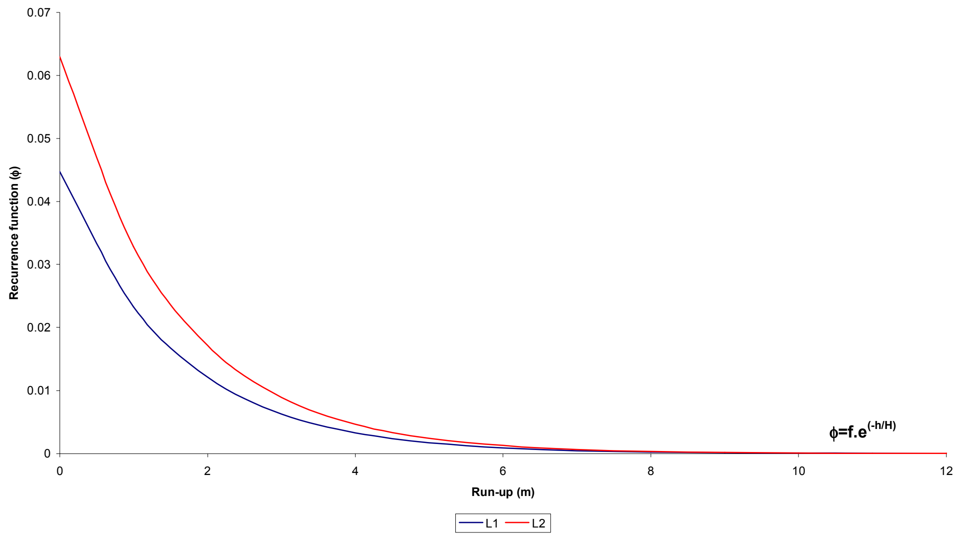


Figure 6.9: Variation of the recurrence function with return period at La Unión.

6.4. TSUNAMI HAZARD ZONING

Tsunami zoning (zonation) is represented by maps indicating the location of areas of different levels of hazard, risk or vulnerability in a tsunamigenic region (UNESCO, [1991]). Tsunami zoning maps are very helpful tool to decide which areas should be evacuated in case of tsunami alert, to established construction limits at the coast and to include criterion that take into account tsunami effects on buildings located at tsunamigenic prone locations.

Determining the tsunami zonation of an area requires first, establishing the average frequency at which flooding would be intolerable, in other words, the return period that an event would exceed, and second, estimating the in-land penetration at which flooding is likely to occur at that return period. (Cox, D., [1979]).

According to the tsunami zoning approach for local tsunamis in Hawaii, proposed by Cox (1979), zoning map construction requires the implementation of the following steps:

a) Calculate the tsunami recurrence function.
b) Compute the expected height for the selected return period.
c) Compute the location of the vertical run-up measure with respect to the shoreline.
d) Obtain the velocity at the measure place in order to compute the total energy of the wave at that location.
e) Obtain the rate of the inland energy loss of the wave at the run-up measure place.
f) Determining the energy profile transverse to the shoreline.
g) Establishing the limit inundation at the interception of the energy profile and the ground profile.

6.5. TSUNAMI HAZARD ZONING MAPS OF EL SALVADOR

Tsunami hazard zoning studies have not been produced in El Salvador. However, coastal segments flooded by tsunamis and those coastal settlements that could be affected by tsunamis have been located. See Figs. 5.1 and 3.8.

According to previous studies, the whole coast of El Salvador is likely to be hit by a tsunami, since it is located closely and almost parallel to the subduction zone between the Cocos and the Caribbean Plates where large earthquakes occur (see Section 4.3.1). The factor that would allow one to associate the level of risk to different areas is the topography of the region (Fernández, M., [written communication]).

6.6. DETERMINISTIC APPROACH IN TSUNAMI HAZARD ASSESSMENT

The main target of deterministic approaches of tsunami hazard assessment is estimating the run-up values and arrival times of a hypothetic event by using numerical modelling. These approaches usually require precise bathymetric data, an adequate numerical model of the source, the propagation phenomena and geological parameters. The need of high quality data input could be a disadvantage especially for regions without such kind of information.

Result values of deterministic approaches are generally expressed as arrival time maps, tsunami front waves, and run-up values at different locations. This visual information is very useful to identify flooded areas, that can be used for building tsunami zoning maps.

Deterministic tsunami hazard approaches have been scarcely implemented in El Salvador. Numerical simulation of the tsunami triggered by the 31 January 1906 Colombian earthquake was recently performed[9]. Results of this approach were shown in Section 4.3.2.

7. TSUNAMI EARLY WARNING SYSTEMS

7.1. OVERVIEW

Tsunami preparedness is the compilation of plans, methods, procedures and actions created by scientists, government officials and the general public for minimizing potential risk and mitigating effects of a possible tsunami (UNESCO, [1991]).

The first step to set a tsunami preparedness scheme is performing a tsunami hazard assessment which should investigate the main causes of historical tsunamis, locate places affected by historical tsunamis, estimate the tsunami hazard in the area and create tsunami zoning maps.

Once tsunami hazard assessment has been implemented and *tsunamicity* of regions has been found to be high, there is the need to implement evacuation plans to avoid massive loss of lives in case of a tsunami strikes. In general terms, *tsunami early warning systems* main objective is issuing warnings of possible tsunami arrivals and their main components are processes as monitoring, communication and decision making activities in order to avoid massive loss of lives if a tsunami occurs.

After the disastrous 26 December 2004 Asian tsunami, people around the world are more aware of the importance of tsunami early warning systems to avoid massive loss of lives.

7.2. TSUNAMI WARNING SYSTEMS

Tsunami early warning systems are a fundamental part of tsunami mitigation schemes. The main targets of these warning systems are first to issue alerts immediately after a tsunami is triggered, second to be accurate when issuing alerts and third being fully functional 24 hours a day. (UNESCO/IOC, [1999]).

Information dissemination is a very important factor of the tsunami early warning system, especially when dealing with local tsunamis whose arrival times are very short. The most efficient dissemination method is using satellite communications but due to the cost of it, some systems use the Internet or telephone to transmit warning information (Fernández, M., [1998]).

According to the type of tsunami that they are responsible to warn for and the *area of responsibility* (AOR) that they cover, these warning systems can be classified as *distant, regional* or *local tsunami warning systems*. Distant tsunami warning systems should provide tsunami alerts between 30 minutes to an hour after a tsunami is generated, whereas regional and local warning systems should issue that information within 10 to 20 minutes and 3 to 5 minutes, respectively (Fernández, M., [1998]).

Nowadays, there is only a distant tsunami warning system that covers the Pacific Basin the *Pacific Tsunami Warning Centre* (PTWC). The PTWC provides tsunami warning information to settlements in the Pacific that are located within several hundred kilometres from tsunami sources. Regional systems warn settlements that are located at least 100 km from tsunami sources. Presently there are two of them operating in the USA and one in Japan, Russia, France and Chile. There are two local tsunami warning systems one in Japan and another in Chile and they warn communities located within 100 km from the tsunami sources (Fernández, M., [1998]). Procedures followed by those institutions for issuing warnings will be described next.

After the disastrous 26 December 2004 Asian tsunami, people around the world are more aware of the importance of tsunami early warning systems to avoid massive loss of lives. Recently, several meetings have been organised by the UNESCO's Intergovernmental Oceanographic Commission (IOC) in order to implement an early warning tsunami system to monitor future events in the Indian Ocean Basin. At this stage (April 2005), there are three main objectives to fulfil with the meetings: first finding out investment and running costs for establishing regional and local warning systems, second assessing public awareness and existing national capacities of building warning schemes and third calling donors for pledging funds to be invested in national or regional warning projects.

7.3. DISTANT TSUNAMI WARNING SYSTEMS

Distant tsunami warning systems are responsible for providing timely information for those locations that are located several hundred kilometres away from tsunami sources. These places are usually struck several hours after the tsunami is generated, therefore tsunami warning can be issued within 30 minutes or 1 hour. Nowadays, there is only one institution that covers distant tsunami warning, its characteristics will described in the sequel.

7.3.1 The Pacific Tsunami Warning Centre

The only institution that presently provides distant tsunami warning information is the Pacific Tsunami Warning Centre (PTWC). In 1948, the Seismic Sea-Wave Warning system was in charge of providing tsunami information warning to the United States coast, in 1966 that institution accepted to extend its *area of responsibility* (AOR) to the whole Pacific Basin and become the Pacific Tsunami Warning Centre (PTWC).

The main aims of the PTWC are to locate and evaluate the magnitude of major earthquakes that occur in the Pacific Basin and determine their tsunamigenic potential, predict tsunami arrival times and run-up values at the coasts and provide timely tsunami warnings. The system operates based on information provided by seismic stations and tidal gauges (further information can be found in the National Oceanic and Atmospheric Administration "NOAA" website, http://www.prh.noaa.gov/itic/tsunami_events/media/currentevents/tsunami_warning_watch_advisory.html)

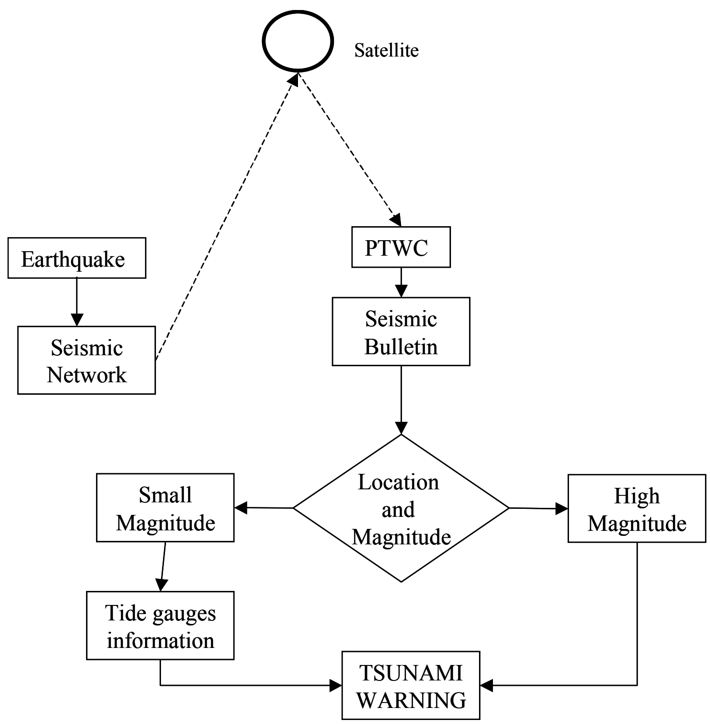
Information provided by this tsunami warning systems is based mainly on data recorded by seismic stations and tidal gauges and it has the form of *warning, warning supplement, watch, bulletins, advisory bulletin, information bulletin* and *warning cancellation.* (NOAA, [http://www.prh.noaa.gov/itic/tsunami_events/media/currentevents/tsunami_warning_watch_advisory.html]). The definition of each term, found in the latter website, is described next

A *tsunami warning* is a message issued to human settlements when it is confirmed that a tsunami has been triggered and that the event is a threat. This kind of warning will be followed by additional *warning supplements* or *bulletins* that will contain updated information of the event.

Tsunami watches are messages to inform that tsunami was probably generated but has not been confirmed and that investigation is being held to verify the tsunami threat, they are based only on seismic information. They are issued when it is likely that human settlements could be hit by a tsunami that has been triggered. Tsunami watches are also followed by *bulletins* that will update related information.

Tsunami *advisory bulletins* are messages issued to human settlements to indicate that they are out of the warning or watch area, or that they would be affected by a tsunami that does not pose any danger to them. Tsunami *information bulletins* are messages issued to inform that a great earthquake has occurred, but the event did not trigger any tsunami.

The procedure that this warning system follows is shown in Fig. 7.1. When a major earthquake occurs, information captured by seismic stations is transmitted via satellite to the PTWC; then a seismic bulletin is issued and disseminated to all the countries of Pacific basin. Depending on the magnitude value and location of the earthquake, a tsunami warning is issued. If the magnitude is small, the need of tsunami warning will depend on tidal gauges information.



Picture 7.1: Methodology followed by the Pacific Tsunami Warning Center.

(Fernández, M., [1998])

7.4. REGIONAL TSUNAMI WARNING SYSTEMS

Regional tsunami warning systems were implemented for human settlements located at least 100 km from tsunami sources. These areas need to be warned within 10 to 20 minutes after the tsunami is generated. Having smaller *areas of responsibility* (AOR), regional tsunami warning systems are able to deal with less data and provide information faster than distant tsunami warning systems.

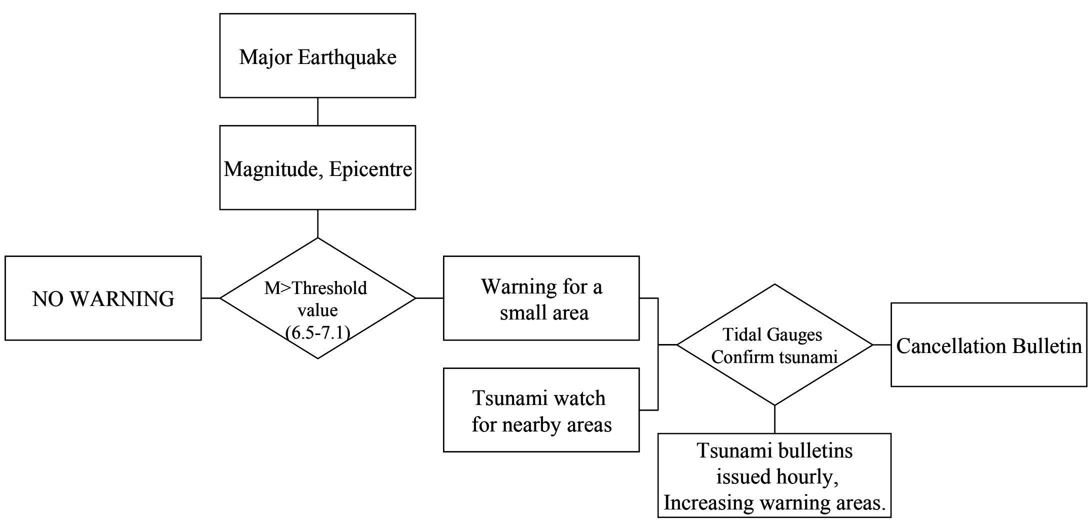
Presently, there are several regional tsunami warning systems operating in the Pacific area in Alaska, French Polynesia, Japan, Russia and Chile. The methodology used by those institutions to issuing tsunami warnings will be described in the sequel.

7.4.1 The West Coast and Alaskan Tsunami Warning Centre (WCATWC)

In 1967, after the great Alaskan tsunamigenic earthquake occurred in 1964, three observatories located at Palmer, Adak and Sitka started operating and share responsibility of the Alaskan Regional Tsunami Warning Centre (ARTWC). After some time of operation, the Adak and Sitka observatories were only responsible for small areas, whereas the Palmer observatory extended its area of responsibility (AOR). In 1973 the Palmer observatory was changed to the National Weather Service of the Alaska Region and was named Alaska Tsunami Warning Centre (ATWC). In 1982, its area of responsibility was extended to cover the coastal regions of California, Oregon, Washington and British Columbia. In 1996 the institution was also responsible for covering warnings at those settlements due to distant sources and it was named the West Coast and Alaska Tsunami Warning Centre (WCATWC).

The institution's aims are to rapidly locate and determine the magnitude of major earthquakes that occurr in the Pacific area, determine their tsunami potential, predict arrival times and run-up values on the coast and provide timely information regarding to the events. The areas of responsibility of the ATWC are the Coastal communities of California, Oregon, Washington, British Columbia and Alaska (NOAA http://www.wcatwc.gov/subpage3.html).

The methodology followed by WCATWC is shown in Fig. 7.2. When an earthquake occurs in the Pacific, the WCATWC determines its magnitude and location. If the magnitude exceeds the threshold values, which usually vary between 6.5 and 7.1, tsunami bulletins with tsunami arrival times are issued to areas located near the epicentre and tsunami watches are sent to nearby areas. Additional tsunami bulletins will be issued at least hourly based on analysis of data provided by tidal gauges stations. If tidal gauges information confirms that a tsunami has been triggered, the tsunami warning is extended to all areas that are likely to be affected. When tidal gauges do not confirm the tsunami, a cancellation bulletin is issued.



Picture 7.2: Methodology followed by the Alaskan Tsunami Warning System.

(Fernández, M., [1998])

7.4.2 The French Polynesia Tsunami Warning System (CPPT)

The French Polynesia Tsunami Warning System (Centre Polynesien de Prevention des Tsunamis CPPT) started operating since 1964, when it was designated to be the institution responsible for tsunami warning. The system gathers information coming from 21 short period stations, 4 broad band stations, 3 long period stations and 2 tidal gauge stations (Fernández, M., [1998]).

The CPPT issues tsunami warning based on the historically observed proportionality of tsunami height and the seismic moment, which depends on the mantle magnitude[20] (M_m) and it is computed using the following relationship $M_m = \log M_0 - 20$, where M_0 is the seismic moment[21]. Hazard level is then established according to values shown in Table 7.1 (Fernández, M., [1998]).

Table 7.1: Magnitude threshold values and hazard level associated.

(Fernández, M., [1998])

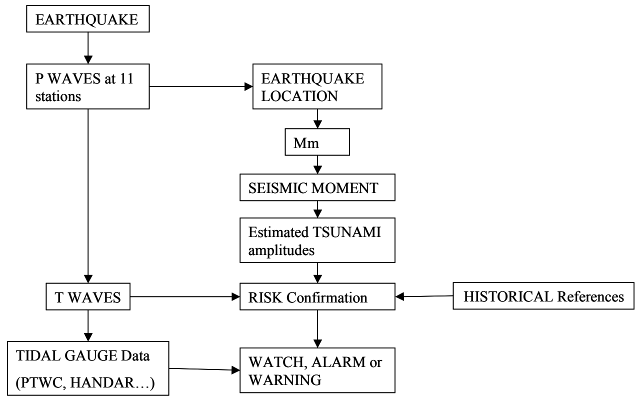
Mm	Mo (dyne-cm)	Hazard level
$M_m<7$	$M_o<10^{27}$	No tsunami risk.
$7<M_m<8$	$10^{27}<M_o<10^{28}$	The generation of large tsunami remains improbable, but a tsunami earthquake cannot be ruled out.
$8<M_m<8.7$	$10^{28}<M_o<5x10^{28}$	A tsunami will probably be generated, but except for the possible case of a tsunami earthquake, should not be catastrophic at teleseismic distances from the epicentre.
$8.7<M_m<9.3$	$5x10^{28}<M_o<2x10^{29}$	Probable generation of a potentially destructive tsunami. Immediate tsunami watch issued if epicentre is in Samoa-Tonga-Kermadec, or otherwise closer than 4000 km.
$M_m>9.3$	$M_o>2x10^{29}$	Generation of very large tsunami, probably very destructive tsunami. Immediate tsunami watch issued for other region.

This regional tsunami warning system has adopted the following methodology (see Fig. 7.3):

- Major earthquakes activate a strong event detector that relies on 11 short period stations. The detector follows a classic multiple criterion of amplitude threshold, frequency content, duration and simultaneity.
- The epicentral region is located using P-time arrivals.
- Location of the earthquake is computed using 3 different long period records at a single station.
- The mantle magnitude M_m and the seismic moment M_o are computed.
- Arrival times and tsunami heights are automatically computed and printed out.
- A geophysicist has to set a tsunami watch or warning depending on the tsunami heights predicted.

[20] The mantle magnitude is based on long-period Rayleigh and Love waves.

[21] The seismic moment is a measure of the size of an earthquake based on the area of fault rupture, the average amount of slip, and the force that was required to overcome the friction sticking the rocks together that were offset by faulting. (http://www.norsar.no/seismology/general/glossary/s.html)

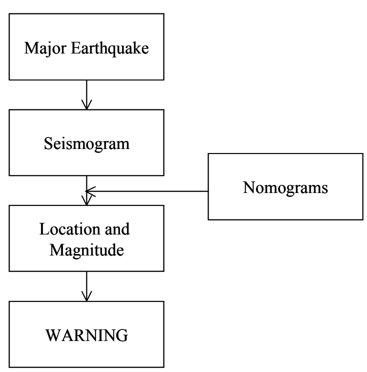


Picture 7.3: Methodology followed by the French Polynesia Tsunami Warning System (CPPT) (Fernández, M., [1998])

7.4.3 The Russian Tsunami Warning System (SPTS)

The Russian Federation Tsunami Warning System started operating between 1956 and 1958 and covers around 4500 km along the Far East Coast of Russia where around 80% of the earthquakes and practically all the Russian tsunamis occur. The Russian Hydrometereological Service with the assistance of the Russian Academy of Sciences is in charge of the three regional centres that compose the system and have the same authority to issue tsunami warnings when threats are found. Each regional centre is responsible for a set area (Fernández, M., [1998]).

The system detects magnitude 7 or greater earthquakes whose epicentres are locate between 150 and 2000 km offshore. Tsunami warnings are set by seismologists and are based on seismograms and nomograms[22]. The process of tsunami warning could take around 10 minutes depending on the seismologist skills, errors up to 100 km when locating the earthquake or 0.2 grades when estimating the magnitude lead to lots of false alarms, which reach about 75% *local tsunami warning system* of the total alarms. A scheme of the methodology used by the Russian Federation Tsunami Warning System is shown in Fig. 7.4.



Picture 7.4: Methodology followed by the Russian Tsunami Warning System. (Fernández, M., [1998])

[22]Nomograms are charts that display mathematical functions. They are constructed so that the relationship between variables can be displayed as a straight line.

7.5. LOCAL TSUNAMI WARNING SYSTEMS

Regional or distant tsunamis are not effective at warning timely human settlements located within 100 km from tsunami sources. This led to the creation of local tsunami warning system in order to quickly warn settlements under tsunami threat, local warning systems generally use satellite telemetry to collect, disseminate, receive and display tsunami warning (Fernández, M., [1998]).

Presently, there are two local tsunami warning systems operating in Japan and Chile. A third one has been proposed in Mexico. The methodology followed by these local warning systems will be described in the sequel.

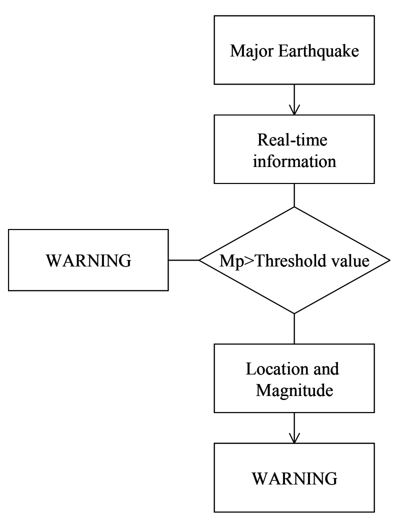
7.5.1 The Japanese Warning System (JMA)

The Japanese Meteorological Agency has been in charge of forecasting tsunamis since 1941. Nowadays a new warning model composed by a new seismograph network, numerical modelling and satellite-based dissemination system has been implemented with the aim of providing tsunami warning within 3 minutes after a tsunamigenic earthquake occurs (Fernández, M., [1998] and (UNESCO/IOC, [1999]). See Fig. 7.5 for a scheme of their methodology.

The seismic network has 150 highly efficient seismographs and 20 STS2 seismometers which provide real-time seismic data. Using P-wave information the magnitude and location of earthquakes are estimated; the value of magnitude indicates if a tsunami could have been triggered by the earthquake.

Once a probable tsunamigenic earthquake has occurred and located, the system starts searching through its database an earthquake simulation that best fit the event. The database contains between 2000 and 3000 simulations, they are contained in 8 files, each file gives predicted tsunami information that is interpolated or linearly approximated to get the final estimated values. Even if the Japanese Warning System is local, it forecasts tsunami sources located within 2000 km from the settlements.

Numerical models used by this system, have the disadvantage of underestimating *run-up* heights nearby the source. The latter could be a problem when the tsunami source is located close to the shore.



Picture 7.5: Methodology followed by the Japanese Tsunami Warning System.

(Fernández, M., [1998])

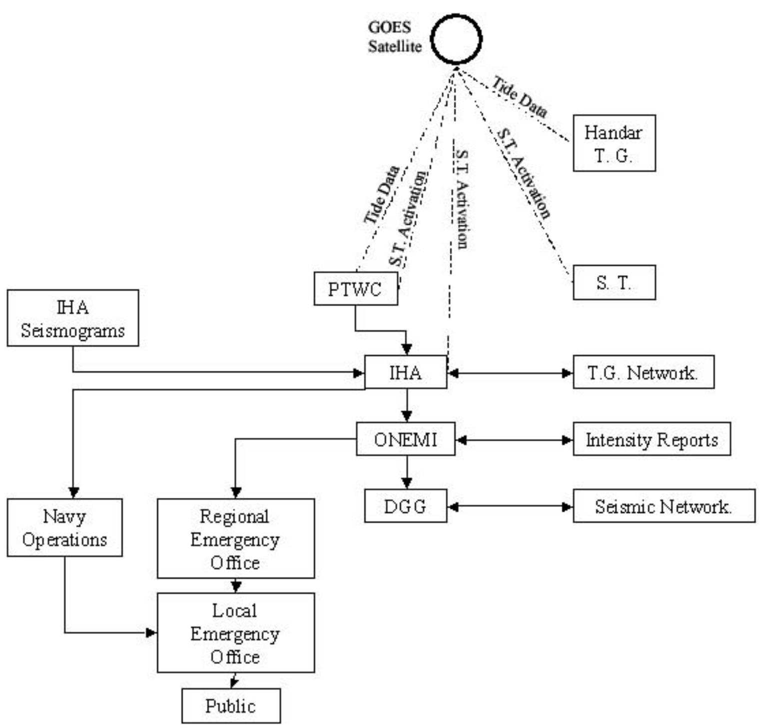
Satellite based communication is used to disseminate tsunami alarms. In case of tsunami warning, the information will be immediately dispatched to municipal offices, news media stations and meteorological observatories. Warnings will include information about seismic intensity, earthquake epicentre and magnitude, tsunami forecast, predicted tsunami arrival times. In case tsunami warnings are no longer valid, clear messages will be sent.

7.5.2 The National Tsunami Warning System of Chile (SNAM)

The National Tsunami Warning System of Chile (Sistema Nacional de Alarma de Maremotos SNAM) started operating since 1964 under the responsibility of the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA). A 31 short-period station network, one TREMORS (Tsunami Risk Evaluation through seismic Moment from a Real-time system) system, 3 six-component broadband stations and 19 tide stations are the equipment that the system uses to operate (UNESCO/IOC, [1999]).

The Pacific Tsunami Warning Centre (PTWC) covers regional tsunamis warnings regarding to the Chilean coasts. Locally triggered tsunamis are forecasted as follows (Fernández, M., [1998]):

- The National Emergency Office (NEO) provides an estimate of the intensity value of the earthquake.
- The Department of Geophysics of the University of Chile provides the magnitude and location of the earthquake.
- If the magnitude is greater than 7.4 or the seismic intensity is higher than VIII on coastal areas, a tsunami warning is issued. See Fig. 7.6 for a scheme of the methodology followed by this institution.



Picture 7.6: Methodology followed by the Chilean Tsunami Warning System.

(Fernández, M., [1998])

7.5.3 The Mexican Tsunami Warning System

A proposal for implementing the Mexican Tsunami Warning System was presented in 1998 after the Colima-Jalisco tsunami hit the country in 1995. The system would work using a broadband seismic station to discriminate near coast and near trench earthquakes and warnings would be issued based on magnitude threshold values that vary between near coast and near trench events (Fernández, M., [1998]).

Several trials were made locating a single broadband station at the Mexican inland closest point to the trench, at around 250 km to the Pacific Coast. Information collected in that way is used to compute the seismic energy magnitude, that is computed from radiated seismic energy and it is related to M_w, and ER that is the ratio of the total energy to the high frequency energy of the earthquake. It was found that near coast events had lower ER values. Near trench events, on the other hand, had very high ER values (Fernández, M., [1998]).

Tsunami warnings would be issued when near trench events (high ER values) have M_E values greater or equal to 6.5, or when near coast events (low ER values) have M_E values greater or equal to 7.3. The process to compute ER and M_E would take approximately 5 minutes (Fernández, M., [1998]).

This method is suitable for countries that do not have a sophisticated or very complete seismic network because it uses only a broadband station. However, seismic data cannot be recorded if the broadband station is placed too close to the earthquake source area (Fernández, M., [1998]).

7.6. PROPOSALS FOR THE CENTRAL AMERICA TSUNAMI WARNING SYSTEM

After the 1992 Nicaraguan tsunami, proposals for establishing tsunami warning systems have been presented by some Central American countries. The first proposal was made in late 1998, as the phase II of the project called “Reduction of Natural Disasters in Central America” held by the Institute of Solid Earth Physics of the University of Bergen, Norway. Another proposal was made in September 2003 by the Coordination Centre for the Prevention of Natural Disasters in Central America (CEPREDENAC).

According with the proposal made in 1998, the methodology explained in section 7.5.3 for the Mexican Tsunami Warning System would be suitable for Central America. This approach proposed that tsunami warnings would be issued by the Institute of Territorial Surveys of Nicaragua (Instituto Nicaraguense de Estudios Territoriales INETER), based on seismic information provided by the Central America Seismological Centre (CASC). INETER would send the alarm to the National Emergency Offices of the countries under warning.

Nicaragua was in charge of formulating the second proposal that was presented in 2003. This methodology is open to comments and suggestion in order to formulate the definitive tsunami warning system methodology. The system is supposed to be multi-national and redundant in order to still get reliable information in case of warning centres damaged during earthquakes (IOC, [2003]).

After the 26 December 2004 Asian tsunami, a new policy of implementing a tsunami early warning system in Central America has emerged. Results have not been materialised yet but the need of minimising tsunami effects in the region is being taken more seriously (Pullinger, C. [written communication]). For example, in Costa Rica inhabitants of Garabito (a population centre at the Pacific Coast) have asked for cooperation to the national seismic network (Red Sismológica

Nacional, RSN: ICE-UCR) and PADF (Organización Panamericana para el Desarrollo) in order to start a tsunami preparedness scheme. Actions to take in the scheme are: tsunami vulnerability and risk analysis, tsunami risk zoning, setting signals in tsunami high-risk zones, educational programmes, upgrading of communication systems, installing several tsunami warning sirens and establishment of a tsunami early warning system (Fernández, M. [written communication]).

7.6.1 First Proposal for the Central American Tsunami Warning System (1998)

This approach proposes to have a warning system that provides timely tsunami warning for the Central American countries. There are two institutions would be involved in the warning issuance, Institute of Territorial Surveys of Nicaragua (Instituto Nicaraguense de Estudios Territoriales INETER) and Central America Seismological Centre (CASC). The latter would be in charge of collecting and storing real time-seismic data, locate earthquakes whose magnitude exceed 4 and issuing daily seismic bulletins for the region. The former would analyse that seismic information and decide if warning must be dispatched (Fernández, M., [1998]).

Tsunami warning systems would follow the methodology listed below:

- Estimated earthquake location is found by CASC using short-period stations and a broadband station.
- Automatically, Mw is computed from the broadband station record.
- Collecting more data, a more accurate location of the earthquake is computed.
- A seismic bulletin is sent to INETER
- INETER evaluates the information and decides if warning should be issued.
- INETER sends tsunami warning to the National Emergency Office of the countries that are likely to be hit by the tsunami.
- The National Emergency office of those countries implements the evacuation plan.

Regional and distant tsunami warnings would be issued by the Pacific Tsunami Warning Centre, The National Tsunami Warning System of Chile or the West Coast and Alaskan Tsunami Warning Centre.

7.6.2 Second Proposal for the Central American Regional Tsunami Warning System (2003)

The proposal for a multi-national regional tsunami warning system was presented in September 2003, as mentioned before. The system is planned to be redundant to avoid failure of warning issuance due to possible destruction of physical components after a major earthquake occurs.

It is important to mention that some of the equipment required for implementing the system is already in place. Sea-level stations would have to be improved in order to transmit real-time information to the PTWC. Personal working in the system would have to be trained in order to analyse data collected from the equipment (IOC, [2003]).

The components that the Central American Regional Tsunami Warning System would have are:

- Coordination Council with two representatives from each country.
- Broadband stations and TREMORS at all national seismic Centres.
- Regional communication network through satellite, the Internet and radio link.
- Special “Units” in the National Systems for Disasters Prevention in each country to transmit warnings to coastal communities.
- National communication to coastal communities.

According to the proposal, comments and suggestions would be very useful to formulate the definitive methodology that the system will adopt.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. CONCLUSIONS

Having performed a probabilistic tsunami hazard assessment of El Salvador based on available historical information, the following conclusions can be pointed:

- El Salvador is likely to be affected by destructive tsunamis due to its high seismic activity and to its geographical location. Main ports and coastal population centres could be hit by local, distant or regional tsunami waves.

- Tsunami waves of several meters in height are expected to occur in the country. Choosing a return period of 250 years, vertical run-up values at Acajutla and La Union could reach 9 and 3 meters respectively. These values are similar to the values registered at the Nicaraguan coast when a damaging tsunami occurred in 1992.

- If a return period of 475 years is chosen, vertical run-up values at Acajutla and La Union could reach 12 and 4 meters respectively. The increasing in vertical run-up values would yield a much more destructive tsunami.

- El Salvador has not implemented a national tsunami warning system, therefore the country is not prepared to warn or evacuate coastal inhabitants in case of local or even regional tsunamis. Distant tsunamis are monitored by the Pacific Tsunami Warning Centre; people could be warned in case of a distant tsunami, but having no tsunami evacuation plans, it is likely that avoiding loss of lives would not be achieved.

- The Salvadorian population is not aware of tsunami hazard.

8.2. RECOMMENDATIONS FOR FUTURE RESEARCH

Tsunamis are not considered a major hazard in El Salvador. Studies on the topic have shown that the country is likely to be hit by destructive tsunamis in the relatively near future. In order to avoid massive loss of lives when a destructive tsunami hit the country, future research should be encouraged. The following ideas are mentioned as recommendations for future research:

- Paleotsunami information could be very useful to improve the accuracy of future probabilistic tsunami hazard assessments.
- Defining upper bound values for estimated run-ups computed according to the probabilistic model implemented in this thesis.
- Further investigation on the possible tsunami caused by the avalanche from the Santa Ana Volcano in the late quaternary age.

- Implementing deterministic tsunami hazard assessments would be very useful to verify if tsunami run-up values contained in the Salvadorian tsunami catalogues are accurate.
- Creation of tsunami hazard, risk or vulnerability zoning map.
- A reliable tsunami early warning system that fills the needs of the country, in other words a warning system able to detect and dispatch information of local and regional tsunamis.
- Implementation of educational plans to increase the tsunami awareness of the inhabitants or at least the coastal inhabitants.
- Elaboration of evacuation plans in case of tsunami.

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APPENDIX A

Tsunami Catalogue of Central America

Molina, E. [1997]

Table I. The Central American Tsunami Catalogue

No	DATE	TIME	EARTHQUAKE SOURCE PARAMETRES			TSUNAMI PARAMETRES			TECTONIC REGION	OCEAN
			Lat	Lon	Ms/I	T	Region	m		
			(N)	(N)						
1	1539-1124	---	---	---	---	L	Honduras Gulf, HON	---	NO-CA	C
2	1579-0316	---	---	---	---	L	Cano Island, CR	---	CO-CA	P
3	1621-0502	---	8.97	79.5	5.6-6.0	L	Panama la Vieja, PAN	---	CANAL DISCONTINUITY	P
4	1798-0222	---	10.2	82.9	VI-VI+	L	Matina, CR	-1	NPDB	C
5	1822-0507	---	9.5	83.0	7.6	L	Matina, CR	-1	NPDB	C
6	1825-02--	---	---	---	5-5.5	L	Roatan Island, Honduras Gulf, HON	---	NO-CA	C
7	1844-05--	---	11.2	84.8	7.0-7.9	S?	Nicaragua Lake, NIC	---	CO-CA	N-L
8	1854-0805	05:30	8.5	83.0	7.25	L	Golfo Dulce, CR	1.5	CO-CA	P
9	1855-0925	---	---	---	6-6.5	L	Trujillo Bay, Honduraas Gulf, HON	---	NO-CA	C
10	1856-0804	---	---	---	7-8	L	Omoa, Honduras Gulf, HON	2	NO-CA	C
11	1859-0826	---	13	87.5	6-6.5	L	Amapala, Fonseca Gulf, HON	1.5	CO-CA	P
12	**1859-1209**	**---**	**13.7**	**89.8**	**7-7.9**	**L**	**Acajutla Bay, SAL**	**1.5**	**CO-CA**	**P**
13	1873-1014	00:05	10.2	80.0	V	L	Colon & Panama Harbors, PAN	---	NPDB	C
14	1882-0907	09:18	10.0	79.0	7.9	L	San Blas Coast, PAN	2	NPDB	C
15	1884-1105	---	4.0	76.0	---	L?	Acandi, Colombia	---	Colombia	P
17	1902-0118	23:23	14.7	91.6	6.3	L?	Ocos, GUA	---	CO-CA	P
18	**1902-0226**	**---**	**13.0**	**89.0**	**7.0**	**?L**	**Pacific Coast GUA-SAL**	**2**		**P**
19	1902-0419	02:24	14.9	91.5	7.5	L?	Ocos, GUA	-1	CO-CA	P
20	1904-0120	14:50	7.0	82.0	5.0	L?		---		P
21	1904-1220	05:42	9.2	82.8	7.45	L	Bocas del Toro, PAN	---	NPDB	C
22	1905-0120	18:23	9.85	84.68	6.8	L?	Coco Island, CR	---	CO-CA	P
23	1906-0131	15:36	1.0	81.3	8.2	R	Tumaco, Euador, San Carlos, PAN,Potrero Bay, CR	---	Ecuador	P
24	**1906-----**	**---**	**---**	**---**	**---**	**T**	**El Salvador Coast, SAL**	**---**		**P**
25	1913-1002	04:23	7.1	80.6	6.7	L	Azuero Peninsula, San Miguel Gulf, PAN	-1	Azuero-Torio F. Z.	P
26	**1915-0907**	**01:20**	**13.9**	**89.6**	**7.7**	**L?**	**El Salvador Coast, SAL**	**0.5**	**CO-CA**	**P**
27	1916-0131	---	---	---	---	T	Panama Canal, PAN	---		P

No	DATE	TIME	EARTHQUAKE SOURCE PARAMETRES			TSUNAMI PARAMETRES			TECTONIC REGION	OCEAN
			Lat (N)	Lon (N)	Ms/I	T	Region	m		
28	1916-0426	02:21	9.2	83.1	6.9	L	Bocas del Toro, PAN	0	NPDB	C
29	**1916-0525**	**---**	**12.0**	**90.0**	**7.5**	**?L?**	**El Salvador**	**---**		**P**
30	1919-0629	23:14	13.5	87.5	6.7	L	Corinto, NIC	---	CO-CA	P
31	1919-1212	---	---	---	---	L	El Ostial, NIC	---	CO-CA	P
32	1920-1209	---	---	---	---	L	Fonseca Gulf	---		P
33	1926-1105	07:55	12.3	85.8	7.0	L	Offshore, NIC	---	CO-CA	P
34	1934-0718	01:36	8.1	82.6	7.5	L	Chiquiri Gulf, PAN	1.5	PFZ	P
35	1941-1205	20:46	8.7	83.2	7.6	L	Pta. Dominical, CR	-1	CO-CA	P
36	1941-1206	---	10.0	85.2	6.9	L	Nicoya Gulf, CR	-2	CO-CA	P
37	**1950-1005**	**16:09**	**10.0**	**85.7**	**7.9**	**L**	**Coasts CR-NIC-SAL**	**-1**	**CO-CA**	**P**
38	**1950-1023**	**16:13**	**14.3**	**91.8**	**7.3**	**L**	**Coasts GUA-SAL**	**-1**	**CO-CA**	**P**
39	1951-0803	00:24	13.0	87.5	6.0	LH	Potosi, Fonseca Gulf, HON	---	CO-CA	P
40	1952-0513	19:31	10.3	85.3	6.9	L	Puntarenas, CR	-3	CO-CA	P
41	1956-1024	14:42	11.5	86.5	7.2	L?	San Juan del Sur, NIC	---	CO-CA	P
42	**1957-0310**	**14:42**	**51.63**	**175.41**	**8.1**	**D**	**Acajutla, SAL**	**---**	**Auletian**	**P**
43	**1960-0522**	**19:11**	**-38.2**	**73.5**	**8.5**	**R?**	**La Union, Fonseca Gulf, SAL**	**---**	**Chile**	**P**
44	1962-0312	11:40	8.0	89.9	6.7	L	Armuelles, Chiquiri G., PAN	-1	CO-CA	P
45	1968-0925	10:38	15.6	92.5	6.0		Pacific Coast	---		P
46	1976-0204	09:01	15.2	89.2	7.5	L	Cortes, Honduras G, HON	-0.5	C	
47	1976-0711	16:54	7.43	78.12	7.0	L	Jaque, Darien, PAN	-1	P	
48	1990-0325	13:16	9.8	84.8	7.0	L	Puntarenas & Quepos, CR	0	P	
49	1991-0422	21:56	9.6	83.2	7.6	L	Bocas del Toro, PAN	1	C	
50	1992-0902	00:16	11.7	87.4	7.2	L	Nicaragua Coast, Bahia de Salinas & Papagayo G., CR	2.5	P	

APPENDIX B

Modified Seiberg Sea-Wave Intensity Scale

ITIC/UNESCO, Tsunami Glossary [http://www.shoa.cl/oceano/itic/frontpage.html]

Table II. Modified Seiberg Sea-Wave Intensity Scale

Intensity		Damage description
1	Very light	Wave so weak as to be perceptible only on tide-gauge records.
2	Light	Wave noticed by those living along the shore and familiar with the sea.
3	Rather strong	Generally noticed. Flooding of gently sloping coasts. Light sailing vessels carried away on shore. Slight damage to light structures situated near the coasts. In estuaries reversal of the river flow some distance upstream.
4	Strong	Flooding of the shore to some depth. Light scouring on man-made ground. Embankments and dikes damaged. Light structures on the coast injured. Bid sailing and small ships drifted inland or carried out to the sea. Coasts littered with floating debris.
5	Very strong	General flooding of the shore to some depth. Quay-walls and solid structures near the sea damaged. Light structures destroyed. Severe scouring of cultivated land and littering of the coast with floating items and sea animals. With exception of big ships all other type of vessels carried inland or out to sea. Big bores in estuary rivers. Harbor works damaged. People drowned. Wave accompanied by strong roar.
6	Disastrous	Partial or complete destruction of made structures for some distance from the shore. Flooding of coasts to great depths. Big ships severely damaged. Trees uprooted or broken. Many casualties.

APPENDIX C

1. Linear Regression under the Maximum Likelihood Method

Having chosen the recurrence function shape as negative exponential, it is expected that the event average vertical run-up values (x) and their experimental recurrence value y (or N, computed as shown below) fit more or less accurately in an exponential curve $y=ae^{-bx}$. In order to be able to apply linear regression analysis to the data, it is necessary to make some transformation to the exponential function to take it into the form y =ln(a)+bx. Where a and b are constants. The steps to transform the data are explained as follows.

Having the run-up values, the events with the same height (h_i) have to be grouped; and the compute the following data for each group:

a) n: Number of events with the same vertical run-up
b) N: Cumulative number of events with vertical run-up greater or equal to h_i
c) Ln N: Natural logarithm of N
d) N': N normalised with ΔT
e) Ln N': Natural logarithm of N'
f) 1/N': Recurrence interval
g) ΔT: Time observing interval

For the current analysis, ΔT is equal to 141 years, which are the years covered by the catalogue data. The values obtained for each hazard scenario are shown in table I.

Table III. Recurrence data at Acajutla and La Union

ACAJUTLA							
x	**n**	**N**	**ln N**	**N'**	**ln N'**	**1/N'**	**var**
0.5	2	7	1.94591015	0.04964539	-3.0028497	20.14	0.00260
0.75	2	5	1.60943791	0.03546099	-3.339322	28.20	0.00313
3	1	3	1.09861229	0.0212766	-3.8501476	47.00	0.00998
4	1	2	0.69314718	0.0141844	-4.2556127	70.50	0.01426
9	1	1	0	0.0070922	-4.9487599	141	0.04714
LA UNION							
x	**n**	**N**	**ln N**	**N'**	**ln N'**	**1/N'**	**Var**
0.175	1	6	1.7917595	0.0425532	-3.1570004	23.50	0.15615
0.5	2	5	1.6094379	0.035461	-3.339322	28.20	0.20064
0.75	2	3	1.0986123	0.0212766	-3.8501476	47.00	0.23864
3	1	1	0	0.0070922	-4.9487599	141	0.72896

Once the parameters of Table I were determined, the linear regression analysis can be performed, and the “h” column will be taken as “x” data vector whereas the “ln(N)” column will be taken as “observed y” data vector.

2.Weighted Least Squares Method

The weighted least square method can be used to models with non-constant error variance, which is indeed the case of tsunami data sets. “In this method of estimation, the deviation between the observed and expected values of y_i is multiplied by a weight w_i chosen inversely proportional to the variance of y_i”(Montgomery, D. and Peck, E. [1982]).

The “first estimation” of the y expected values, should be computed through the least squares method, as follows:

a) Taking the vertical run-up column as the “x vector” and the “y observed” vector as “d”. These vectors dimensions are (NX1) being N the number of data sets recorded.

b) The matrix G can be computed as, $G \cdot m = d$, where m is called the model parameter vector defined as $[m_1, m_2, m_3, \ldots, m_N]^T$. Whenever a linear regression is performed, all m_i are equal to one (1). Then, the matrix “G” takes the form:

$$G = \begin{bmatrix} d_1 & 1 \\ d_2 & 1 \\ \vdots & \vdots \\ d_N & 1 \end{bmatrix}$$

c) The first estimated parameters can be computed as

$$m_{est} = [G^T G]^{-1} \cdot G^T \cdot d$$

Then, m_{est1} and m_{est2} are the function parameters (the intercept and slope of the line, respectively). Then the first “y estimated” vector can be computed as

$$y_i = m_{est1} + m_{est2} \cdot x_i$$

d) The variance of the “y estimated” will have the form $[var]=[v_1, v_2, \ldots, v_N]^T$, and each component of that vector can be computed as:

$$var_i = \frac{Se_i}{\sigma^2}$$

$$Se_i = \sqrt{\frac{y_{OBS}(x_i) - y_{EST}(x_i)}{N-2}}$$

$$\sigma^2 = \sum_i^N Se_i$$

e) Finally, the parameters variance matrix can be computed as

$$[var(m_{est})] = [(G^T G)^{-1} \cdot G^T] \cdot [var(d)] \cdot [(G^T G)^{-1} \cdot G^T]^T$$

Once the first y vector is estimated, the weighted least squares method is applied following the steps mentioned below.

a) Taking the height column as the “x vector” and the “first y estimated” vector as “d”.

b) The matrix G can be computed as, $G \cdot m = d$, where m is defined as $[1, 1, 1, \ldots, 1]^T$, as explained before. Then, the matrix “G” takes the same form:

$$G = \begin{bmatrix} d_1 & 1 \\ d_2 & 1 \\ \vdots & \vdots \\ d_N & 1 \end{bmatrix}$$

c) The intersect and slope of the function can be computed as

$$m_{est} = [G^T W_e G]^{-1} \cdot G^T W_e \cdot d$$

Where W_e is the weight matrix and it is computed as $W_e = [var(d)]^{-1}$ and [var(d)] is the variance vector computed for the “first y estimated” vector. (See above).

d) And finally, the variance of the parameters can be computed as
$[\mathrm{var}(m_{est})] = [(G^T W_e G)^{-1} \cdot G^T W_e] \cdot [\mathrm{var}(d)] \cdot [(G^T W_e G)^{-1} \cdot G^T W_e]^T$

The parameters contained in the covariance matrix, $\mathrm{var}(m_{1est})$ and $\mathrm{var}(m_{2est})$ are respectively the standard deviation of the intercept and slope of the recurrence function in its linear form.

Having performed the previous analysis, the parameters of the asymptotic recurrence function ($\phi_{(h_o)} = f_{(x)} \cdot e^{\frac{-h}{H^*(x)}}$) can be easily computed as:

$$m_{1est} = \ln(f)$$

$$m_{2est} = -\frac{1}{H^*}$$

APPENDIX D

Computer Code for the Tsunami Hazard Assessment of El Salvador

```
%TSUNAMI HAZARD ASSESSMENT OF EL SALVADOR
%PROBABILISTIC APPROACH
%Msc in Seismic Engineering
%ROSE SCHOOL, 2004
%==============================================================%
%input data
load la_union.dat;                    %height and natutal logarithm of cumulative frequency data
data=la_union;

%reading data
d   =data(:,1);                        %height values (x)
y   =data(:,2);                       %frequency data (y observed)
sd =data(:,3);                        %covariance of the height values
N   =length(d);

%y= a+ bx (first estimation)
G     =[ones(length(d),1),d];
Gl=inv(G'*G)*G';
mestl =Gl*y;
al    =mestl(1,1);                    %intercept least squares
bl    =mestl(2,1);                    %slope least squares
yestl =al+bl*d;                       %y values estimated under LS

%Weighted least squares
We    =inv(diag(sd.^2));
Gw=inv(G'*We*G)*G'*We;
mest2 =Gw*y;
aw    =mest2(1,1);                    %intercept weighted least squares
bw    =mest2(2,1);                    %slope weighted least squares
yestw =aw+bw*d;                       %y values estimated under WLS

%Regression reliability
   %Weighted Least Squares
   SDw =sqrt((sum((yestw-y).^2))/(N-2));                   %Standard deviation WLS approach
   rw_2=sum((yestw-mean(y)).^2)/sum((y-mean(y)).^2);       %regression coefficient WLS

%Recurrence function values
H=-1/bw;
f=exp(aw);

%Plotting
```

```
%Linear Regression (WLS)
figure('Name','Experimental data regression','NumberTitle','off');
plot(d,yestw,'b');
hold on
plot(d,y,'rx','markersize',24);
hold on
errorbar(d,yestw,sd,'k.');
hold on
plot(d,yestw-SDw,'k--');
hold on
plot(d,yestw+SDw,'k--');
axis([0,3.1,-5.5,-2.5])
xlabel('Maximum vertical run-up (m)','fontsize',12);
ylabel('Cumulative frequency','fontsize',12);
title('Regression of the experimental values','fontsize',14);
legend('Regression curve','Experimental data','Deviation');
label=strcat('Standard deviation =',num2str(SDw,3));

%Recurrence Function
heights=[];
fi=[];
for i=0:2:50
   heights=[heights i];
   fi=[fi f*exp(-(i/H))];
end
figure('Name','Recurrence function','NumberTitle','off');

plot(heights,fi,'b-');
hold on
xlabel('Vertical Run-up (m)','fontsize', 12);
ylabel('Recurrence function   \phi(h)','fontsize',12);
title('Recurrence function  \phi(h)','fontsize',14);
label = strcat('H*',num2str(H,3));
```