TSUNAMI HAZARD ASSESSMENT OF AMERICAN SAMOA

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Abstract

A preliminary probabilistic tsunami hazard assessment (PTHA) was conducted for American Samoa. The pilot study utilized NEOWAVE to model propagation of tsunamis across the ocean and inundation at the shores of Pago Pago, which is home to key infrastructure of the territory. While the framework is compact and computationally efficient, it takes into account important near-field sources along the Tonga-Kermadec trench that significantly influence the 100 and 500-year inundation. The annual exceedance probability of the earthquake is determined from either the moment magnitude, Mw, or the observed rate of occurrence. The regional rate of Mw 9+ earthquakes is derived from observed global values scaled by local tectonic parameters such as the relative length, convergence rate, and obliquity of convergence of the fault; the rate of Mw 7.3-8.9 earthquakes is based on the global Gutenberg-Richter rate scaled by local tectonic parameters except for Mw 7.3-7.4 and 8.0-8.4, which are functions of the local observed values in historical events. A sensitivity analysis shows that tsunami inundation from far-field, Pacific Rim sources only have secondary effects in the probabilistic framework. The modeled far-field tsunamis with the most impact on American Samoa provide a basis for emergency response in the case of large Mw 9+ earthquakes in those regions. The 100 and 500-year inundation zones provide a rational account of the exposure to tsunamis, and the analysis lays for the groundwork for conducting a full regional PTHA of American Samoa.
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Chapter 1

Introduction

The 2009 Samoa tsunami was devastating. It claimed 189 lives in Independent Samoa, Tonga, and American Samoa and caused extensive damage to coastal infrastructure and communities (Dominey-Howes and Thaman 2009). Post-event survey records show maximum localized run-up on Tutuila of 15 m (Jaffe 2009). The occurrence of the 2009 event stresses the need for a comprehensive evaluation of the tsunami hazard in American Samoa in order to develop effective mitigation plans. American Samoa currently relies on an ad-hoc evacuation map delineated by the 50 ft (15 m) elevation contour (The American Samoan Government 2012). The 2004 Sumatra and 2011 Tohoku tsunamis both produced run-ups exceeding 30 m in the near-field (Borrero et al. 2006; Mori et al. 2011). Paleotsunami evidence points to the prehistoric occurrence of comparable events around the South Pacific (e.g., Goff and Dominey-Howes 2009; Goff et al. 2010; Goff et al. 2011a, b). Given the occurrence of the 2004 and 2011 near-field events and evidence that similar events have occurred in the South Pacific, an evacuation zone defined by the 15 m contour likely underestimates the potential tsunami run-up from a near-field subduction zone source like the Tonga-Kermadec Trench. Conversely, the 15 m contour may overestimate the run-up associated with comparably sized far-field tectonic events – one size does not fit all, in other words. A more rigorous approach is required to develop appropriate evacuation zones given the earthquake potential of the Tonga-Kermadec Trench. Probabilistic tsunami hazard analysis (PTHA) provides a mechanism to determine the likelihood of a suite of tsunamigenic events based on a logic-tree approach.

PTHA can broadly take one of two forms: an empirical analysis of run-up from a tsunami catalog for a specific site or from numerically modeled tsunami run-up and inundation from tsunami sources to the site. An empirical approach relies on establishing site-specific tsunami hazard through observed run-up frequency-size distributions. A numerical approach, on the other hand, relies on deforming the ocean water column in response to external forcing – typically seafloor deformation in the case of tsunamis –
and propagating the corresponding wave landward through the application of the shallow-water equations.

The empirical approach, pioneered by the work of Soloviev (1969), seeks to establish the probability of exceedance for a range of run-up values for a site from observed data. The advantage of the empirical approach is that no knowledge of the tsunami source is needed. Several drawbacks, however, limit its range of application. The method requires a comprehensive tsunami catalog, which does not exist for American Samoa, and it says nothing about the inundation or flow velocities, both of which, independent of run-up, can have substantial impacts on tsunami prone coastal communities (Geist and Parsons 2006). A numerical approach, therefore, is needed for conducting a PTHA of American Samoa.

The genesis of numerical PTHA is with the work of Houston and Garcia (1974) and Garcia and Houston (1975), and was continued by others (e.g., Lin and Tung 1982; Rikitake and Aida 1988; Ward and Asphaug 1999; Ward 2001; Annaka et al. 2007; Burbidge et al. 2008; González et al. 2009; Priest et al. 2010). Numerical PTHA was adapted from probabilistic seismic hazard analysis (PSHA). PSHA seeks to relate the likelihood of ground shaking of some magnitude being exceeded to the likelihood of occurrence of the corresponding earthquake (Cornell 1968). Likewise, PTHA seeks to relate the likelihood that a tsunami of some magnitude will be exceeded due to the occurrence of a corresponding earthquake. Unlike ground shaking, however, site specific tsunamis may have their sources from more than one local and/or distant seismic source. A numerical PTHA, therefore, requires an adequate catalog of tsunami sources, typically earthquakes, to make substantive inferences about tsunami recurrence intervals. A thorough knowledge of the seismic setting is required for numerical PTHA.

A rich but short global record exists of historic earthquakes since ~1900 AD. A number of global catalogs have been developed that provide varying ranges of validity and catalog density, the origin of which is the Gutenberg and Richter catalog and the current culmination of which is the Engdahl and Villaseñor centennial catalog (Gutenberg and Richter 1956; Abe 1981; Abe 1984; Abe and Noguchi 1983a, b; Båth and Duda 1979; Geller and Kanamori 1977; Pacheco and Skyes 1992; Engdahl and
Villaseñor 2002). The Engdahl and Villaseñor centennial catalog can be supplemented with Mw 7+ earthquakes up to 2013 using sources from the US Geological Survey (http://earthquake.usgs.gov/earthquakes/search/) to provide a complete catalog of Mw 7+ earthquakes from 1900-2013. The brevity of the historic catalog and the relative infrequency of large megathrust earthquakes, the ones that produce large tsunamis, have prompted the integration of other data sources to supplement the historic dataset. Paleotsunami datasets serve as a powerful tool for the validation and calibration of results obtained from PTHA. They can also provide a baseline for the maximum probable tsunami for a site – an invaluable tool for tsunami hazard assessment.

Several endeavors have been made to numerically reproduce the 2009 Samoa tsunami (e.g., Jaffe et al. 2011; Fritz et al. 2011; Roeber et al. 2010; Zhou et al. 2012; Didenkulova 2013). Far fewer efforts, however, have been made to model other tsunamis in American Samoa, largely due to a dearth of accurate run-up and inundation data. One notable exception is Okal et al. (2004) – they conducted hydrodynamic simulations of an 1865 earthquake on the Tonga Trench in order to constrain the location and magnitude of the event. However, the steep insular slopes and the abrupt transition to the shelves and reefs at the coast require special attention in modeling of tsunami impacts. This study utilizes the NEOWAVE (Non-hydrostatic Evolution of Ocean Waves) model, which caters to the challenging physical environments of tropical islands, and is used around the world for tsunami hazard assessment (Yamazaki et al. 2009, 2011).

A comprehensive earthquake catalog, an understanding of the paleotsunami setting, and a suitable tsunami model provide the tools for a complete hydrodynamic analysis of the probabilistic tsunami hazard for American Samoa, an analysis that will serve to increase the safety and wellbeing of its population. The goal is to evaluate the tsunami threat to American Samoa and develop a computationally compact method for a corresponding PTHA. As a pilot study, the PTHA is used to develop 1/100 and 1/500 annual exceedance probability (AEP) limits of tsunami inundation at Pago Pago, which is home to key infrastructure of the territory.
Chapter 2
Regional Setting

American Samoa, which consists of six islands, is part of the Pacific Island Countries (PICs), a region covering ~ 1.2 million km$^2$ of ocean. The 2010 census indicates a total population of 55,519 for American Samoa, a fifth of whom live in Pago Pago, on Tutuila, the area of focus for this study. Figure 1 shows the regional setting. The regional tectonic attributes are apparent. The Tonga-Kermadec subduction zone, a convergent plate boundary, extends from the North Island of New Zealand for approximately 2,800 km to the north-northeast and terminates in an arcuate section 200 km to the southwest of American Samoa. The subduction zone consists of two parts, the Kermadec Trench to the south and the Tonga Trench to the north of the Louisville Ridge, which is a hotspot-generated seamount chain running southeast from the subduction zone (Ballance 1989). The northern portion of the trench is characterized by a subduction transform edge propagator (STEP) that results in its arcuate shape and a near vertical dip-slip section on the tear of the oceanic plate (Govers and Wortel 2005). The northern arcuate section of the Tonga-Kermadec Trench can be identified on Figure 1 as the northwest trending section of the trench to the southwest of Independent Samoa. Figure 1 also shows the historic Mw 7+ earthquakes that have occurred regionally. There have been no historic Mw 8.5+ events on the Tonga-Kermadec Trench, and the seismic activity increases toward the northern part of the trench.

2.1. Seismicity

The convergence rate at the Tonga Trench is the greatest on Earth, varying from 16.4 cm/yr at 21°S, 20.5 cm/yr at 19°S, and the fastest in the north at 24 cm/yr at 16°S (Oliver and Isacks 1967; Bevis et al. 1995; Pelletier et al. 1998). The shallow subduction zone is characterized by thrust faulting with slip nearly normal to the trench axis (Bonnardot et al. 2007).

Tsunami energy propagates away from a source perpendicular to the strike of a fault (e.g., Barkan et al. 2009; Gica et al. 2008). Events on the northern arc, therefore, have the greatest impact on tsunami genesis in American Samoa; moving south along the
trench, the impact of comparable size events is less severe. The primary focus of this study on tsunami sources, therefore, will be on the northern arcuate section, although other sources will be considered, especially for the larger events.

There have been a total of seven Mw 8+ earthquakes on the Tonga-Kermadec Trench since 1900, two of which comprised the 2009 Samoa-Tonga great earthquake doublet as shown by Lay et al. (2010) and four of which produced noticeable tsunamis (> 0.3 m above MSL on the coast line). The 2009 Samoa sequence of earthquakes occurred on the northern terminus of the Tonga Trench in a STEP geometry. The event started with normal extensional faulting on the outer-rise (Mw 8.1) which triggered a shallow thrust subduction doublet on the trench (Lay et al. 2010). Okal at al. (2011) reviewed tsunamigenic predecessors to the 2009 event that include the 1917 (June 26th) and 1919 (April 30th) earthquakes. Localized run-ups of 20 m and maregram readings of 90 cm wave heights (vs. 70 cm amplitudes for the 2009 event) were reported on Tutuila for the 1917 event (Okal et al. 2011; Pararas-Carayannis and Dong 1980). The occurrence of the 1917 and 2009 events suggests that the 2009 tsunami represents a 100 yr event. Run-up heights for the 1919 event were 2.0-2.5 m for Tutuila (Pararas-Carayannis and Dong 1980). The arrival of the seismic waves at a recording station in Japan indicate that the 1919 earthquake was a normal faulting event, and its error ellipse, as estimated by Okal et al. (2011), indicates that it may have occurred on the outer-rise of the trench slope, similar to the first earthquake in the 2009 sequence of events.

2.2. *Paleotsunamis*

Goff et al. (2011a) compiled a thorough review of paleotsunamis in the PICs, the motivation of which rested in the occurrence of the 2009 Tonga earthquake and concomitant Samoa tsunami. The historic tsunami record in the PIC is rich but short and scattered. Prior to the arrival of Europeans, Polynesian history was transmitted through generations by oral tradition; there was no written language. As a consequence, the only tsunamis that are known about prior to the arrival of Europeans are from oral accounts and the presence of paleotsunami proxies.

Numerous sites around the PICs indicate the occurrence of an event around 1450 AD. Carbon ($^{14}$C) dating of sand deposits, stories of people dying and the gods washing large
boulders ashore, and the termination of Polynesian seafaring all point to a very large tsunami occurring in the South Pacific around 500 yrs ago (Goff et al. 2011a, b; Goff et al. 2012). Contemporaneous with this event was the eruption of the Kuwae Volcano in Vanuatu, which released at least 100 km$^3$ of shallow-water deposits (Witter and Self 2007). Given the diameter of the caldera, 5000 m, and an assumed water depth in the near-shore of 200 m, the subsequent tsunami would have a period of $T = \frac{2 \times \text{diameter}}{\sqrt{gh}} = 3.75 \text{ min}$ (Rabinovich 1997). With a period of 3.75 min, the resulting shallow-water wavelength is $L = T\sqrt{gh} = 10,000 \text{ m}$, or twice the diameter of the caldera. The wave goes through a reverse shoaling process to reach the open ocean of 6,000 m depth and travels as a series of dispersive waves losing amplitude farther away from the source.

There were events recorded around the PICs, far enough away (3400 km for the Cook Islands) that the wave amplitude would have diminished so much that the deposition of the paleotsunami proxies was likely from a different tsunamigenic source, the most likely candidate being from the Tonga-Kermadec or Vanuatu trenches.

In addition to the 15th Century event, Goff et al. (2010) identify events from 6500 and 2800 yrs BP on the North Island of New Zealand. Goff et al. (2011a) also identify numerous paleotsunami events at 1200, 2800, 3750, and 4200 yrs BP on Vanuatu. Okal et al. (2004) indicate that the 1865 Tonga earthquake (Mw 8.4) did not produce any significant tsunami deposits in the region, so a larger event on the scale of a Mw 9+ megathrust earthquake likely produced the deposits that have been observed from tsunamis 500, 1200, 1650, 2000, 2800, 3750, and 4200 yrs BP. This results in a recurrence interval of ~600 years in the region typical of catastrophic events.
Chapter 3

Global Mw 9+ Earthquakes

The total length of subduction zones in the world is ~43,500 km according to von Huene and Scholl (1991), most of which circumscribe the Pacific Basin. Figure 2 shows the Pacific Basin and the earthquakes that occurred during 1900-2013. With the exception of the 2004 Sumatra earthquake, all of the historic Mw 9+ earthquakes and the sources of the largest tsunamis, occurred in shallow subduction zones around the Pacific Basin. The majority of historic Mw 8+ tsunamigenic earthquakes, too, have occurred in the Pacific Basin. Out of 80 world-wide Mw 8 or greater earthquakes since 1900, only five have occurred outside of the Pacific Basin. Pacheco and Skyes (1992) find that shallow subduction zones expend approximately 90% of the total tectonic energy release. Figure 3 shows the cumulative seismic moment for earthquakes since 1900, which indicates that approximately 80% of the world’s seismic energy release comes from subduction zone events. With 90% of subduction zone seismic energy release occurring in the shallow zone, 80% of all seismic energy release occurring in subduction zones, and the majority of tsunamis finding their genesis in shallow subduction zone earthquakes, the focus of this study is on shallow (<= 50 km depth) subduction zone earthquakes.

3.1. Historic Mw 9+ Earthquakes

The five Mw 9+ earthquakes since 1900 include the 1952 Kamchatka (Mw 9.0), the 1960 Chile (Mw 9.5), the 1964 Alaska (Mw 9.2), the 2004 Sumatra-Andaman (Mw 9.3), and the 2011 Tohoku (Mw 9.1), all of which produced large tsunamis locally and in the far-field. A thorough review of the source mechanisms for each earthquake has been conducted. Unfortunately, each of the earthquakes is unique and they cannot be lumped together into a single characteristic Mw 9+ event.

Butler (2014) reviewed thirty-three studies of the five Mw 9+ events, which are summarized in Table 1. All rigidity values have been standardized to the Preliminary Reference Earth Model (PREM) value of 44.1 GPa (Dziewonski and Anderson 1981). The fault characteristics for the five events vary widely – there are variations between the events that include dimensional, magnitude, the presence (or lack) of asperities, and slip
distribution. For example, the Tohoku event exhibited the largest observed maximum slip, but its dimensions are relatively compact, the Sumatra event had significantly larger dimensions than the rest and relatively small average slip. The Kamchatka event exhibited larger slip down-dip from the trench, whereas the Tohoku event exhibited more slip toward the trench. The takeaway from the analysis is that, amongst the five Mw 9+ events, there are five types of events, each possessing unique characteristics.

The characteristics for each type of Mw 9+ earthquake are generalized for implementation in PTHA. Table 2 shows the dimensions and associated slip distributions. All types have a total fault width of 100 km consisting of two 50-km segments and total fault lengths evenly divisible by 100 km, except the Tohoku-like event, which is evenly divisible by 50 km. Type I represents a Kamchatka-like event with a fault length of 600 km, an average slip of 5 m, and 85% of the slip on the down-dip half of the fault. Type II represents a Chile-like event with a uniform slip of 35 m across a fault length of 700 km. Type III represents an Alaska-like event with a fault length of 700 km, uniform slip across the depth, an average slip of 12 m, and a symmetrical slip that increases from the ends toward the center and decreases in the center. Geodetic inversion indicates that the slip is skewed toward one end and not perfectly symmetrical. However, given the need to represent seismic events as succinctly as possible, the slip is represented symmetrically. Type IV represents a Tohoku-like event with a length of 350 km, an average slip of 19 m, a non-uniform slip across the depth, and a non-uniform, symmetrical slip across the length. Finally, Type V represents a Sumatra-like event, long at 1400 km with a uniform slip of 10 m over the whole fault.

3.2. Paleotsunamis

Following the 2004 Sumatra tsunami, more effort was dedicated to characterizing paleotsunamis. Prior to the 2004 event, only one Mw 8+ earthquake had occurred on the Sumatra Subduction Zone, a Mw 8.2 in 1977. Without some indication that a Mw 9.0+ mega-thrust earthquake could occur on the subduction zone, no one would ever have predicted the occurrence of the 2004 event. Paleotsunami evidence, however, exists that indicates the occurrence of very large tsunamis originating from the Sumatra subduction zone, as well as from Japan, Chile, and North America.
Stratigraphic analysis of core samples from the Aceh Province of Sumatra indicates that an event of the same magnitude as the 2004 earthquake occurred 6500 to 7000 yrs BP (Grand Pre et al. 2012). A couple of events occurred about 4000 and 3000 yrs BP (Dura et al. 2011). These three events happened in about 3500 yrs for a recurrence interval of 1167 yrs. No paleotsunami deposits have been unearthed in Sumatra that indicate the occurrence of tsunamis during the late Holocene (4500 yrs BP to present), for which the net emergence of the coast of northwest Sumatra has been the reason (Dura et al. 2011). There is evidence of large tsunamis occurring in the Indian Ocean, however, from stratigraphic analysis of sediments in some coastal lagoons in southeastern Sri Lanka (Jackson 2008). The analyses indicate that, including the 2004 event, there have been six tsunamis in the Karagan Lagoon in the past 5500 yrs for a recurrence interval of 1100 yrs, which corresponds relatively well with the pre-Holocene events.

The Pacific coast of Japan has a long and recorded history of tsunami occurrence (Horikawa and Shuto 1983). A total of 106 tsunamis were recorded in Japan from 416 to 1978 AD, and the 2011 event adds one more. The largest event on the Sendai Plain prior to the 2011 tsunami, and the only one comparable to it, was the 869 Jōgan tsunami. The 869 tsunami caused extensive flooding, damage, and death across the Sendai Plain. Numerical simulations of the event, conducted by Sugawara et al. (2013), indicate that the inundation area of the Jōgan tsunami is comparable to the inundation area of the 2011 event, which constrains a Tohoku-like event to a recurrence interval of 1142 yrs (Minoura et al. 2001).

Cisternas et al. (2005) reconstructed 2000 yrs of coseismic subsidence and tsunami record for the Río Maullín estuary in Chile. They found that the 1575 earthquake and tsunami were comparable to the 1960 event for a recurrence interval of 385 yrs. Six other events preceded the 1960 event, for a total of 7 events prior to 1960 in the last 2000 years. Including the 1960 and 2010 Mw 8.8 Chilean earthquake, nine large (> Mw 8.0) earthquakes have occurred in the last 2000 yrs on the South American subduction zone for a recurrence interval of 222 yrs. Only four of the events, however, produced tsunamis of the same magnitude as the 1960 event for a recurrence interval of ~666 yrs for the 1960 earthquake and tsunami.
Tree-ring evidence in Northern Oregon and Washington and geologic evidence in Japan of a tsunami from the Pacific Northwest indicates that a very large tsunami occurred from a rupture on the Cascadia subduction zone around 1700 AD (Jacoby et al. 1997; Satake et al. 1996). In addition to the large event around 1700 AD, subsidence, paleotsunami evidence, and liquefaction features from ground shaking all indicate that great earthquakes occur on average every 500 yrs on the Cascadia subduction zone (Clague 1997; Darienzo et al. 1994; Goldfinger et al. 2003).

The global paleotsunami record points to a recurrence interval of 500-1000 yrs on large subduction zones for great tsunamis, the source of which is Mw 9+ earthquakes. Knowledge of these recurrence intervals provide a basis on which to determine an appropriate method for establishing recurrence rates for Mw 9+ earthquakes on the Tonga-Kermadec Trench.
Chapter 4

Recurrence Rates

The recurrence rates for different ranges and types of earthquakes are analyzed based on the historic occurrence of such events. This study evaluates five groups of events: a Mw 7.3 STEP event, Mw 7.5-7.9, Mw 8.0-8.4 (thrust and outer-rise), Mw 8.5-8.9, and Mw 9+ events. If a local record exists for a range of earthquakes, the observed rate is used to establish a rate for modeled events. Otherwise, the rates are compared with several alternative methods and the best method is chosen to assign rates to the events on the Tonga-Kermadec Trench. For all the ranges of magnitudes, discreet values represent a range of 0.1 Mw, which is consistent with the Engdahl and Villaseñor catalog (2002). Paleotsunami records are used to determine the most appropriate method used for establishing the local rates of Mw 9+ earthquakes. The Mw 7.3 event is evaluated as a local characteristic earthquake and its recurrence is based on the observed rate. The Mw 8.0-8.4 events are evaluated based on observed local historic events. The 8.5-8.9 and 9+ events, which lack local records, are evaluated based on global historic events. The Mw 7.5-7.9 earthquakes, although they are represented locally, are also evaluated based on global historic events. The recurrence rates are applied to all of the modeled events; through PTHA, the rates are then applied to the resulting inundation maps produced from each model run, from which 1/100 and 1/500 AEP inundation limits are produced.

4.1. Sources of Uncertainty

Uncertainty comes in two flavors, aleatory and epistemic. Epistemic uncertainty, in general, can be decreased by increasing the amount of data available to describe a system. Higher resolution bathymetry, for example, decreases the uncertainty associated with numerical inundation calculations (Matsuyama et al. 1999). Epistemic uncertainty (e.g., fault width, length, depth, exact location, slip distribution, etc.) can be accommodated in PTHA by the use of a logic tree. A logic tree starts with a single event that has a probability of occurrence with branches spanning out from the event to account for the epistemic uncertainties.
Aleatory uncertainty, however, cannot be decreased by increasing the data density, e.g., the tide level at the time of a tsunami (Mofjeld et al. 1997). Aleatory uncertainty is typically directly incorporated into the rate calculations by relating the cumulative probability that some hazard variable (such as maximum run-up) will be exceeded to the expected value and variance of the hazard variable (Geist and Parsons 2006). The expected hazard variable and variance are determined from regression of existing data. Adequate data rarely exist that can sufficiently link the expected hazard (e.g., maximum run-up) to an aleatory uncertainty. The typical solution to this problem is to conduct a Monte Carlo simulation of random variability of the uncertain parameter. However, given the computational cost of utilizing a non-linear model like NEOWAVE, the aleatory uncertainties in this study are either accommodated by assuming the worst-case scenario (in the case of tides where higher high water (HHW) is assumed) or in a logic tree (in the case of slip distribution), which produces a simplified and more systematic sampling of the uncertain parameter than a Monte Carlo simulation.

4.2. Methods of Apportioning Rates

The local rate of occurrence of earthquakes can be estimated by three different methods. The most well known method is the Gutenberg-Richter (G-R) frequency-magnitude relationship. The second method apportions the rate of earthquakes based on the local convergence rate. The third method scales the global rate by the subduction zone length, the convergence rate, and the obliquity of convergence. Each of these methods are evaluated in the context of the Tonga-Kermadec Trench and applied appropriately to the five groups of events to determine the recurrence rates for each range of modeled earthquake magnitudes.

4.2.1. Gutenberg-Richter Frequency-Magnitude Relationship

The G-R relationship states that the magnitude and frequency of earthquakes in a seismically active region follows a power law distribution of the form:

$$\log_{10}N = a - bM,$$  \hspace{1cm} (1)

where \(N\) is the number of earthquakes with a magnitude greater than or equal to \(M\) and \(a\) and \(b\) are scaling constants. The relationship is surprisingly robust with a \(b\)-value
typically close to 1.0. There are a couple of statistical methods used to calculate the b-value – the least squares method and the maximum likelihood estimation (MLE) method (Aki 1965; Tinti and Mulargia 1987). The MLE method is the preferred approach to estimating the b-value since the G-R relationship is non-Gaussian. Aki (1965) derived a simple means of calculating the b-value using the following equation, which falls out of the MLE method:

\[ b = \frac{\ln(N)}{\sum_{i=1}^{N}(M_i - M_z)} \]  

(2)

where \( M_z \) is the minimum magnitude of the earthquake catalog and \( M_i \) are the binned magnitudes. A problem with this approach is that earthquakes are discretized into 0.1 Mw increments so that the lowest bin, the minimum of the catalog and containing the most earthquakes, has a disproportionate affect on the calculated b-value. Tinti and Mulagaria (1987) provide a solution to this in the form of a “success parameter,” \( p \), which is given by the following relationship:

\[ p = 1 + \frac{\Delta m}{\sum_{i=1}^{N}(M_i - M_z)} \]  

(3)

where \( \Delta m \) is the magnitude increment. The beta-value is related to \( p \) by the following formula:

\[ \beta = \frac{\ln(p)}{\Delta m} \]  

(4)

where \( b = \frac{\beta}{\ln(10)} \). The standard deviation of the beta-value is given by the following formula:

\[ \sigma = \frac{1-p}{\ln(10) \sqrt{\Delta m \cdot \sqrt{N \cdot p}}} \]  

(5)

from which the confidence intervals for the beta-value can be determined from \( z \)-tables and applied to the b-value using the relationship between the beta-value and the b-value.

4.2.2. Recurrence Intervals from Convergence

The second method attempts to equate earthquake frequency of occurrence to local convergence rates. This method has been mentioned or applied in several studies (e.g., Geist and Parson 2006; Thio et al. 2007; Burbidge et al. 2008). The method evaluates the
average rate of occurrence of a characteristic event based on how much slip is taken up on a fault coseismically and how much energy release is taken up by the range of magnitudes that the characteristic event represents. In other words, taking aseismic slip and global energy release by magnitude range into account, the convergence rate should say something about the rate of occurrence of earthquakes on a subduction zone.

4.2.3. Proportion of Global Rate

The third method, advanced by Burbidge et al. (2008), proposes that every part of the global subduction system contributes randomly to the rate of Mw 7.5+ earthquakes. In other words, scaled by length and convergence rate, all faults on the planet are equal with regard to their proclivity to produce Mw 7.5+ earthquakes. This is a direct consequence of the spatial homogeneity of earthquake occurrence. Longer subduction zones have more room for large earthquakes, faster converging zones fault to failure more often, and faults with a lower obliquity angle partition a greater proportion of their strain release to the dip-slip portion of the faulting mechanism. The local rate can be determined by scaling the global rate by length, convergence rate, and the angle of obliquity.

Google Earth was used to measure the piece-wise length (L_i) of the world’s faults. The convergence rate (ν_i) and azimuth for every section was determined primarily from the UNAVCO Plate Motion Calculator (“Plate Motion Calculator” 2012) using the 2010 MORVEL 2010 model of DeMets et al. (2010). The obliquity (Ω_i) is the angle between the azimuth and the trench-normal direction. The total length of the world’s subduction zones, \( \sum L_i \), is about 43,500 km. The gross convergence is the summed product of length and convergence rate, \( \sum L_i \nu_i \), and the net convergence area rate incorporates obliquity by multiplying the summed product of length, convergence rate, and the cosine of obliquity, \( \sum L_i \nu_i \cos (\Omega_i) \).

4.3. Mw 9+ Earthquakes

The paleotsunami record points to Mw 9+ earthquakes producing tsunamis that closely correspond to the 1/500 AEP (annual exceedance probability) inundation limit. These events also likely influence the 1/100 AEP inundation limit. Apportioning the rates for the Mw 9+ events, therefore, is the most important aspect of the study and, because of
the paucity of local Mw 9+ earthquakes, the one that has the most uncertainty. The three methods for apportioning rates are applied to Mw 9+ earthquakes and compared against paleotsunami records. The method that provides the best agreement with paleotsunami evidence is used to assign rates to Mw 9+ events on the Tonga-Kermadec Trench.

Five Mw 9+ earthquakes occurred since 1900: the 1952 Kamchatka (Mw 9.0), the 1960 Chile (Mw 9.5), the 1964 Alaska (Mw 9.2), the 2004 Sumatra-Andaman (Mw 9.3), and the 2011 Tohoku (Mw 9.1). All of them were shallow, megathrust earthquakes in subduction zones. None of these events occurred on the Tonga-Kermadec Trench. Evidence of large paleotsunamis in the PICs, however, indicates that such events have occurred in the past in the South Pacific, although the source region(s) have not been tightly constrained. Given the subduction rate, the proximity to American Samoa, and the tsunamigenic potential of the Tonga-Kermadec Trench, the possibility of a Mw 9+ megathrust earthquake occurring on the trench cannot be ruled out.

Kagan (1999) showed that earthquake recurrence rates are universal regardless of spatial distribution, all other aspects, such as depth and fault type, being equal. There are some notable exceptions such as swarms following a large earthquake (Sykes 1970). Furthermore, numerous earthquake recurrence models have been developed on the assumption that earthquake occurrence follows a Poisson process (e.g., Cornell 1968; Esteva 1969; Merz and Cornell 1973). Given a Poisson process and spatial homogeneity of earthquake occurrence, Mw 9+ earthquakes will continue at a rate of 5/113 per year based on the recurrence rate over the last 113 yrs.

4.3.1. G-R Method

Since 1900, 551 earthquakes have occurred worldwide with a magnitude >= 7.0 Mw, 52 with a magnitude >= 8.0 Mw, and 5 with a magnitude >= 9.0. Utilizing the Tinti and Mulagaria method, the global G-R b-value is 1.03, which is consistent with the accepted value of 1.0. Table 3 shows the b-values and corresponding rates for Mw 7+, 8+, and 9+ earthquakes and the recurrence rates for large tsunamis from the paleotsunami record for Chile, Tonga-Kermadec, Japan, and Cascadia. Again, these rates are just for shallow subduction zone earthquakes.
The use of the local G-R relationship to estimate the local rate of occurrence for Mw 9+ earthquakes results in substantial over-prediction of the recurrence rate of Mw 9+ earthquakes for the Japan, Sumatra-Andaman, and Chile regions compared to the characteristic rate associated with large paleotsunamis. Only one shallow Mw 7+ earthquake has occurred on the Cascadia Subduction Zone for the duration of the catalog, so any meaningful analysis of the expected rate of Mw 7+ earthquakes is rendered useless by the lack of data on the subduction zone. The rate of occurrence of Mw 9+ earthquakes obtained from the local G-R relationship, therefore, does not represent the paleotsunami record well and should not be used for determining local rates of Mw 9+ earthquakes.

4.3.2. Convergence Method

The rate of convergence for the Tonga Trench is ~24 cm/year (Pelletier et al. 1998). Assuming a Mw 9.0 like the 1952 Kamchatka earthquake that averaged about 5 m of displacement, the convergence rate would suggest that the Tonga-Kermadec Trench should see 0.25 m-yr\(^{-1}\)/(5 m) x 100 = 5 Mw 9+ earthquakes a century. The observed rate, however, is substantially lower. Taking into account the coupling coefficient, which Pacheco et al. (1993) determined to be 0.14, the expected coseismic slip is 14% of the total slip. The return period of a Mw 9+ event on the trench, taking aseismic slip into account, would be 5 x 1/7 = 0.714 events per century, or 1 Mw 9+ earthquake every 140 yrs, which is still an underestimation of the return period of Mw 9+ events on the trench given the observed and paleotsunami record. The proclivity of seismic energy release to occur in Mw 9+ events can also be applied to the convergence method. Figure 3 shows the cumulative seismic moment for the planet since 1900. The Mw 9+ earthquakes account for almost two-thirds of the world’s subduction zone seismic energy release, which puts the recurrence interval at 140 yrs/(2/3), or 210 yrs, again, an underestimation of the recurrence interval based on historic and paleotsunami evidence. For other subduction zones whose coupling coefficients are higher but have lower convergence rates, the same line of reasoning also results in overestimation of the rate of occurrence of Mw 9+ earthquakes. The convergence method, therefore, cannot be used to ascribe local recurrence rates to Mw 9+ earthquakes.

4.3.3. Proportion of Global Rate
The local rates for the Japan, Sumatra-Andaman, Chile, and Cascadia subduction zones are determined from the global rate scaled by local subduction zone lengths, convergence rates, and angles of obliquity. The results are compared against the paleotsunami record to determine the efficacy of the approach. The Japan Trench is used to outline the methodology and Table 4 shows the results for the other trenches.

The section of the Japan Trench in the northeast part of Honshu, Japan is approximately 600 km long with a convergence rate of 9.2 cm/year. The Tohoku gross convergence rate is 1.9% of the world’s gross convergent rate, which gives an AEP of Mw 9+ earthquakes on the trench of $5/113 \times 0.0191 = 1/1189$. The AEP for the net convergence rate (2.2% of the global rate) is 1/1027, the average of the two being 1/1108, which agrees well with the observed AEP of 1/1142 from the 869 AD Jogan tsunami to the 2011 Tohoku tsunami. As Table 4 indicates, the rates for Japan and Sumatra-Andaman are over predicted by the proportion method, but not by much, especially compared to the other methods. The rates for Chile and Cascadia are under predicted, but again, not by much compared to the other methods.

Of the three methods examined, the local rate of Mw 9+ earthquake occurrence is best approximated by scaling the global rate of occurrence of Mw 9+ earthquakes by the convergence rate, fault length, and obliquity of convergence. Mw 9+ earthquakes influence PTHA the most out of any other range of earthquake magnitude values. With a clear idea of the expected rates of occurrence for Mw 9+ earthquakes on the Tonga-Kermadec Trench, a PTHA can be effectively conducted for the region.

4.3.4. Tonga-Kermadec

The Tonga-Kermadec subduction zone has not experienced a Mw 9+ earthquake in modern history. The system, given its high convergence rate and size, however, will likely host a Mw 9+ earthquake in the future. The proportion of the global convergence rate that the Tonga-Kermadec Trench consumes permits an estimation of the rate of occurrence of Mw 9+ earthquakes based on a global rate of 5/113. Each characteristic global historic event in Table 2 is assumed to have the same probability of occurrence, so each is equally weighted as $1/5^{th}$ on a branch of a logic tree.
The rates associated with the occurrence of the five types of Mw 9+ earthquakes on the Tonga-Kermadec Trench are derived from the trench’s share of the world’s tectonic subduction. The proportion of the trench’s share of subduction is a function of the length of the subduction zone (1400 km for the Tonga portion), the convergence rate (16-24 cm/yr), and the obliquity of convergence (-5° to 23°, averaged). The proportion of the Tonga system’s subduction to the world’s subduction is about 8.93%. For the Type V earthquake, the resulting AEP on the Tonga Trench is .0893*1/113, or 1/1265. The same logic applies to the other four types, all of which can fit into the northern most 700 km of the trench, as well as the southern 700 km section of the trench down to the Louisville Ridge.

The proportion of the global subduction that the northern portion of the trench consumes is about 4.7%, which results in an AEP of 1/113 x .047, or 1/2402, for each event. Two of the Type IV events, 350 km long, can fit into the northern section for an AEP of 1/4804 per section. The same method is applied to the southern 700 km section of the Tonga Trench, the proportion of the global subduction of which it consumes is 4.2%. A logic tree outlining the decisions and weights applied to each decision is shown in Figure 4. Since all of the source parameters are well constrained for the five Mw 9+ events, the only aleatory uncertainties addressed with the logic tree are the locations and types of the events. Except for the difference in convergence rates of the Tonga and Kermadec trenches and the northern and southern portions of the Tonga Trench, the branches in the logic tree are all assigned a weight of 0.5. For the northern and southern portions of the Tonga Trench, the branches are assigned values based upon the proportion of the net convergence that they consume of the Tonga Trench. The weights assigned to the Tonga and Kermadec portions of the system are determined from their respective net convergence relative to global net convergence.

4.4. Mw 8.0-8.9 Earthquakes

Table 5 outlines the historical events and their locations, mechanisms, and literature references. The rates of earthquakes Mw 8.0-8.4, which have a history of occurrence on the Tonga Trench, are based on historical events. The rates of Mw 8.5-8.9 earthquakes are based on the global G-R rate.
4.4.1. Mw 8.1 Outer Rise Events

Two historical earthquakes \( \geq \) Mw 8.0 on the Tonga Trench were outer rise events – the 1919 and 2009 events. The 1919 event occurred about 390 km south of the 2009 event. Lay et al. (2010) modeled the 2009 event based on a fault length of 130 km. Assuming the 1919 event is similar to the 2009 event, the total length between the two events is \(~520\) km. With a fault length of 130 km and two events occurring in 90 yrs, the AEP of Mw 8.1 outer rise events is \(2/90\), or \(1/45\). The modeled outer rise event is assumed to be like the 2009 outer rise event, whose source parameters have been relatively well constrained, so the only aleatory uncertainty that needs to be accommodated is location. Four 130 km long earthquakes can fit in 520 km between the 1919 and 2009 events, which gives a rate for each event of \(1/45 \times 1/4 = 1/180\).

4.4.2. Mw 8.0 and 8.4 Interplate Thrust Events

There have been two Mw 8.0 thrust events since 1900: the 1917 event and the 2009 doublet, a span of 92 yrs. The distance between the two events is \(~400\) km (including the potential fault lengths themselves). The AEP of Mw 8.0 thrust events in the northern arcuate section of the trench is \(2/92\), or \(1/46\). Aleatory uncertainty in the parameterization of the event can be accommodated by varying the width, location of faulting along the dip, the length, and the distribution of slip along the dip. Figure 5 shows the logic tree for Mw 8.0 thrust events. The displacement is represented by distribution over 1) the up-dip 50 km, 2) the down-dip 50 km, 3) 100 km along the dip (with variations in distribution: uniform, 2:1 in upper:lower tiers, 1:2 in upper:lower tiers), 4) 150 km lengthwise, and 5) 200 km lengthwise. All of them are equally weighted, so the total number of fault combinations is 10, which leads to an AEP of \(1/92 x 1/10\), or \(1/920\).

The only other historical event \(\geq\) Mw 8.0 to occur along the Tonga Trench was the 1865 Mw 8.4 event located at \(-20^\circ\)N. The magnitude of the earthquake was constrained by observed tsunamis in Rarotonga and the Marquesas (Okal et al. 2004). If the earthquake could have happened anywhere north of the 1865 event, the distance being \(~900\) km including the potential length of the fault, and assuming a magnitude scaled length of 300 km, the AEP is \(1/148\) over the 900 km distance. Figure 6 shows the logic tree for the Mw 8.4 thrust events. Like the Mw 8.0 events, aleatory uncertainty is
accommodated by varying length, location, and slip distribution. Three 300 km long events can fit in 900 km of fault with 6 potential fault configurations for length and slip distribution, which leads to an AEP of $1/148 \times 1/3 \times 1/6 = 1/2664$.

4.4.3. Mw 8.5-8.9 Interplate Thrust Events

The AEP of Mw 8.5-8.9 earthquakes, which do not have a modern history of occurrence on the Tonga-Kermadec Trench, are determined by the scaling the global G-R rate by the net relative subduction of the north Tonga Trench. Figure 7 shows a plot of the return period for increasing values of magnitude for the world and for the northern portion of the Tonga Trench. The black step plot represents the world catalog of Mw 7+ earthquakes from 1900 to 2013, which consists of 551 events. The blue line is a log-linear fit to the Mw 7+ catalog events. The red and purple lines are the convergence scaled proportions of the global recurrence interval for the Tonga and North Tonga trenches, respectively. Based on the plot, the recurrence interval of Mw 9+ events on the North Tonga Trench is ~500 yrs, which is in agreement with the paleotsunami record. Figure 8 shows the logic tree for the Mw 8.5 earthquake, which, aside from the G-R rate for the specific magnitude, is the same for all Mw 8.5-8.9 earthquakes. The aleatory uncertainty is accommodated by varying the length and location of the earthquake. The weight assigned to the length is in proportion to the length of the fault and the length of the North Tonga or Tonga Trench, whichever one it fits into. The slip is varied from uniform, 2:1 – deep:shallow, and 1:2 – deep:shallow with equal 1/3 weights.

4.5. Mw 7.3-7.9 Earthquakes

Smaller events are included to fill in the higher recurrence rate values, namely recurrence rates greater than 1/100 per year. The AEP of Mw 7.5-7.9 earthquakes can be determined by either utilizing the local G-R rate or the global G-R rate scaled by the relative subduction of the north Tonga Trench. Similar to the Mw 9s, which have not historically occurred on the Tonga Trench, the local G-R rate is likely not indicative of the Tonga Trench’s prehistoric subduction rate (given its convergence rate). For example, the b-value obtained by examining earthquakes on the Tonga-Kermadec system since 1900 is 0.79, well below the accepted value of b ~ 1.0, which means that the earthquake rates are overestimated by using the local rate. Therefore, the global G-R rate scaled by
the relative subduction of the north Tonga Trench is used to determine the rate of Mw 7.5-7.9 earthquakes. Table 6 shows the scaled recurrence rates for earthquakes Mw 7.5-7.9 for the North Tonga Trench and Mw 8.5-8.9 for the Tonga Trench.

Events are modeled down the trench from the arc southward until they have a negligible impact on the AEP inundation lines. Figure 9 shows the logic tree for the Mw 7.9 earthquakes. The Mw 7.8 earthquakes have the same logic tree structure as the Mw 7.9 earthquakes. The only difference between the Mw 7.5-7.7 and the Mw 7.9 is that a branch for width variation is removed. Aleatory uncertainty is again accommodated by varying the lengths, widths, and slip distributions, where appropriate.

4.5.1. STEP Events

The propensity for relatively large events (> Mw 7) to occur along the Tonga Trench increases dramatically toward the northern STEP portion of the trench. The STEP region is likely too far west to produce any appreciable tsunamis, however. The event is included in the analysis to provide a complete representation the Tonga-Kermadec subduction system. The largest earthquake in the STEP region was a Mw 7.3 – other STEP regions show similar levels of seismicity (Govers and Wortel 2005). The AEP for the event is 1/113 since 1900. A vertical dip-slip (δ = 90°) and the PREM rigidity value is assumed for the slip calculation.

4.6. Circum-Pacific Tele-tsunamis

The impacts of cirum-Pacific events are evaluated by modeling the average characteristic Mw 9+ earthquake around the subduction zones that circumscribe the Pacific Basin. In particular, earthquakes from the following subduction systems are evaluated: South Chile, Chile, Ecuador, Central America, Alaska-Aleutian, Kamchatka, Japan, the Philippines, and Vanuatu.
Chapter 5  
Numerical Modeling

Tsunamis result from a disruption in the ocean water column, the development of a corresponding free-surface gravity wave, and subsequent radial propagation of the wave away from the source. Tsunami waves are characterized by long wavelengths and fall into the shallow-water regime where the depth is less than $1/20^{th}$ of the wavelength. Their genesis can be from a number of events including both submarine and terrestrial landslides, volcanic activity, meteor strikes, and, most commonly, seismic activity. This study only considers tsunamis generated by earthquakes as the other sources tend to produce tsunamis that only have near-field effects or very low probability of occurrence.

5.1. Tsunami Model and Set-up

NEOWAVE is used to model the tsunamis from source to the site (Yamazaki et al. 2009, 2011). NEOWAVE is a shock-capturing, dispersive wave model for tsunami generation, basin-wide evolution, and run-up. It utilizes non-hydrostatic pressure and vertical velocity terms to describe dispersion and time-varying seafloor deformation. Hydraulic jumps and discontinuities are accommodated in the model with a momentum-conserving advection scheme. A two-way grid-nesting scheme uses the Dirichlet condition to enable wave dispersion and discontinuities across inter-grid boundaries.

The governing equations that describe the depth-integrated, non-hydrostatic flow are derived from the incompressible Navier-Stokes equations and the continuity equation. Let $R$ and $\Omega$ denote the radius angular velocity of the earth and $g$ the gravitational acceleration. The governing equations, which have the same structure as the non-linear shallow-water equations, take the following form in a spherical coordinate system:
\[
\frac{\partial U}{\partial t} + \frac{U}{R\cos\phi} \frac{\partial U}{\partial \lambda} + \frac{V}{R} \frac{\partial U}{\partial \phi} - \left(2\Omega + \frac{U}{R\cos\phi}\right)V \sin\phi = -\frac{g}{R\cos\phi} \frac{\partial \zeta}{\partial \lambda} - \frac{1}{2R\cos\phi} \frac{\partial q}{\partial \lambda} - \frac{1}{2D} \frac{\partial (\zeta - h + \eta)}{\partial \lambda} - n^2 \frac{g}{D^{1/3}} \frac{U\sqrt{U^2 + V^2}}{D}
\]

\[
\frac{\partial V}{\partial t} + \frac{U}{R\cos\phi} \frac{\partial V}{\partial \lambda} + \frac{V}{R} \frac{\partial V}{\partial \phi} + \left(2\Omega + \frac{U}{R\cos\phi}\right)V \sin\phi = -\frac{g}{R} \frac{\partial \zeta}{\partial \phi} - \frac{1}{2R} \frac{\partial q}{\partial \phi} - \frac{1}{2D} \frac{\partial (\zeta - h + \eta)}{\partial \phi} - n^2 \frac{g}{D^{1/3}} \frac{V\sqrt{U^2 + V^2}}{D}
\]

\[
\frac{\partial W}{\partial t} = \frac{q}{D}
\]

\[
\frac{\partial (\zeta - \eta)}{\partial t} + \frac{1}{R\cos\phi} \frac{\partial (UD)}{\partial \lambda} + \frac{1}{R\cos\phi} \frac{\partial (V\cos\phi D)}{\partial \phi} = 0
\]

where \(U\), \(V\), and \(W\) are the depth-averaged velocity components in the \(\lambda\), \(\phi\), and \(z\) directions; \(\zeta\), \(\eta\), \(h\), and \(D\) are surface elevation, seafloor vertical displacement, water depth, and flow depth; \(q\) is the non-hydrostatic pressure on the seafloor; \(n\) is the Manning’s coefficient of roughness. Because of the assumption of a linear velocity
distribution, $W$ is the average of $w$ at the sea surface and seafloor given, respectively, by (10) and (11) as:

$$w = \frac{\partial \zeta}{\partial t} + \frac{u}{R \cos \phi} \frac{\partial \zeta}{\partial \lambda} + \frac{v}{R} \frac{\partial (h - \eta)}{\partial \phi} \text{ at } z = \zeta \quad (10)$$

$$w = \frac{\partial \eta}{\partial t} + \frac{u}{R \cos \phi} \frac{\partial (h - \eta)}{\partial \lambda} - \frac{v}{R} \frac{\partial (h - \eta)}{\partial \phi} \text{ at } z = -h + \eta \quad (11)$$

The depth-integrated non-hydrostatic equations describe wave dispersion through the non-hydrostatic and vertical velocity.

### 5.2. Grid Set-up and Bathymetry

Four levels of nested grids were used in NEOWAVE and are described in Table 7. There are eight sub-domains used in modeling American Samoa. For the sake of showing the efficacy of the probabilistic approach used in this study, the only sub-domain evaluated is the Pago Pago sub-domain. There is a historical record of tsunami inundation in Pago Pago off which the 2009 model is calibrated. The Tonga Trench and American Samoa grids are variable in size because of varying needs for grid sizes – smaller grids are computationally cheaper, so the smallest grids possible were used for each run based upon the footprint of the fault. A schematic of the first and second nested grids is shown in Figure 10. The other 2 layers of nested grids are structured similarly. The grid scheme permits information exchange across the boundaries every level-1 time step, which includes wave breaking and dispersion across the inter-grid boundaries. NEOWAVE provides a numerical formulation for modeling the tsunamis hydrostatically, which utilizes an explicit scheme for the solution of the governing equations. In terms of computational costs, the hydrostatic version is much cheaper than the non-hydrostatic version. For the purposes of this study, which is laying the groundwork for a non-hydrostatic tsunami hazard assessment of American Samoa, the hydrostatic option is used.

Numerous sources of data exist for bathymetry and topography. Table 8 identifies the sources of the data, as well as their coverage. Four sources of bathymetry/topography are used for modeling. The LiDAR point cloud data was gridded to a 5 m resolution. All of
the vertical datums are standardized to mean sea level (MSL) and the horizontal datum is WGS84. The only correction made to the data around Pago Pago was to some exposed reef on the east shore of Pago Pago Harbor.

5.3. Translation of Mw to Seafloor Deformation

The earthquakes described above need to be cast in terms of seismic source parameters for tsunami modeling. The Gutenberg-Richter magnitude-energy relationship provides a link between earthquake moment magnitude and seismic moment. The work of Aki (1966) and Kanamori (1977, 1978) provide a link between seismic moment and fault area and slip. Scaling relationships provide simple linear scaling of moment magnitude to fault length and width. Logic trees provide a means of accommodating uncertainty and assigning probabilities to various modeled earthquakes, which can be directly translated to the probability of the resulting tsunamis occurring. Source units provide a physical framework on which to model the earthquakes (including standard source parameters such as dip angle, strike angle, etc.). A planar fault model provides the mechanism for translating seismic source parameters to seafloor deformation, from which tsunamis are modeled as shallow-water waves and produce inundation maps. With a suite of earthquakes, their rates, and a powerful tool in for inundation modeling (NEOWAVE), probabilistic inundation maps can be developed using a PTHA framework.

5.3.1. Gutenberg-Richter Magnitude-Energy Relationship

The Gutenberg-Richter magnitude-energy relationship was borne out of the need to parameterize the size of an earthquake using short-period seismographs (Richter 1935). The parameter that Richter proposed was the local magnitude scale, $M_L$, the logarithm of the observed amplitudes of seismic waves for earthquakes in Southern California. The local magnitude scale was based on observations of short period (0.1 to 2.0 s) seismic waves from nearby earthquakes, so Gutenberg (1945) extended the method to distant earthquakes whose periods are on the scale of 20 s.

The longer period seismic waves required a new magnitude scale, which Gutenberg coined the surface-wave magnitude, $M_s$. In addition to $M_s$, Gutenberg introduced the body wave magnitude, $m_b$, which applied to P and S body waves, whose periods are from
1.0 to 10.0 s. With all three scales, a range of seismic wave periods could be parameterized based on the frequency spectrum. After some work, Gutenberg and Richter (1956) finally related the energy of seismic waves, $E$ (expressed in Ergs), to the surface-wave magnitude with the following formula:

$$\log_{10} E = 1.5M_s + 11.8$$  \hspace{1cm} (10)

A problem with this approach became apparent when a number of large seismic events occurred in the ‘50s and ‘60s. The physical size of the earthquakes was very large compared to the earthquakes in the previous 50 years of instrumented observations – on the scale of 1000 km. Large rupture areas take longer to fault, about 400 s for a 1000 km long fault (Kanamori 1986). The original Gutenberg-Richter relationship, which parameterizes energy release in terms of surface-waves whose periods are ~20 s, underestimates the energy released during an event whose seismic frequency spectrum extends an order of magnitude larger than short-period surface-waves.

Aki (1966) solved the shortcomings of using the surface-wave magnitude by relating seismic moment, $M_0$, to the energy released during an earthquake. The seismic moment is defined by the following relationship between $\mu$, the rigidity of the faulting rock, $D$, the average slip on the fault, and $S$, the fault area:

$$M_0 = \mu DS$$  \hspace{1cm} (11)

The seismic moment can be related to the energy release, $E$, by the following formula (Kanamori 1977):

$$E = \frac{M_0}{(2\mu/\Delta\sigma)}$$  \hspace{1cm} (Kanamori 1977),

where $\Delta\sigma$ is the average stress drop in an earthquake. The value for $2\mu/\Delta\sigma$ is approximately $2\times10^4$, which leads to the following relationship between the moment magnitude, $M_w$, and the seismic moment (Kanamori 1978):

$$M_w = (\log_{10} M_0 / 1.5) - 10.7$$  \hspace{1cm} (13)

Equation 13 provides a direct link between the moment magnitude of an earthquake and the source parameters that are used to describe the slip, which is the key parameter in the
planar fault model. All rigidity values used in this study assume the PREM value of 44.1 GPa (Dziewonski and Anderson 1981).

5.3.2. Scaling Relationships between Earthquake Magnitude and Source Parameters

Earthquake source characteristics are complex and difficult to constrain within a simple framework. Given the uncertainty with earthquake source parameterization and the averaging effect that a probabilistic approach has on the outcome of an analysis, scaling relationships are used to relate the earthquake magnitude to the source parameters, the fault dimensions in particular, for Mw 7.5-8.9. The source parameters for the Mw 9+ and Mw 7.3 earthquakes are defined by the characteristic earthquakes described in chapter 3.

A number of studies have sought to relate earthquake source parameters with each other and with the magnitude of an earthquake (Tochner 1958; Chinnery 1969; Kanamori and Anderson 1975; Acharya 1979; Wyss 1979; Bonilla et al. 1984). The work of Wells and Coopersmith (1984) set the standard for the estimation of source parameters for crustal earthquakes. The primary source of tsunamis, however, is subduction zone earthquakes. In response to the need for scaling relationships between source parameters and earthquake magnitude in subduction zones, Blaser et al. (2010) utilized a large database of earthquakes and their source parameters taken from Wells and Coopersmith (1994), Geller (1976), Scholz (1982), Mai and Beroza (2000), and Konstantinou et al. (2005) to develop subduction zone and fault type specific scaling relationships.

Blaser et al. (2010) isolated shallow subduction zone events and identified differences between thrust, normal, and strike-slip faults and compared the logarithm of the lengths and widths to the corresponding moment magnitude via a linear regression to estimate the linear coefficients of the fit. The relationship between the moment magnitude, Mw, and the dependent variable Y takes the following form:

\[ \log_{10} Y = a + b M_w. \] (14)

where \( a \) and \( b \) are linear coefficients depending on the dependent variable, which is fault width and length (in km) in this case.
5.3.3. Source Units and a Planar Fault Model

For the purpose of providing a structured system of faults for modeling earthquakes on the Tonga-Kermadec Trench, an approach similar to Gica et al. (2008) is used. The zone is divided into 100x50 km sections following the SIFT sub-fault models. Figure 1 shows the distribution of the 100 km long fault segments. For Type IV events, the faults are split in two length-wise to create 50x50 km subfaults. The subfaults are tiled two width-wise to produce a total width of 100 km and tiled along the entire length of the trench. The subfaults are used to reconstruct the seismic source for the purposes of modeling the tsunamis with NEOWAVE. Also shown in the figure are the faults consistent with the 2009 outer rise event and the STEP fault. The final fault dimensions are constrained by the requirement that they are multiples of either 100 or 50 km since the fault tiling is based on 100 km long SIFT faults.

Okada (1985) provided an analytical solution to approximating the deformation of the earth’s surface in response to an earthquake at depth. His solution relies on the assumptions that the rock in which the earthquake occurs is homogenous, that the rock is perfectly elastic, and the fault occurs across a plane, all reasonable assumptions given how poorly seismic parameters are constrained. Figure 11 shows the Okada Planar Fault Model. The deformation on the earth’s surface is a linear function of the slip and fault dimensions (length and width), and is also influenced by the depth, strike, latitude, longitude, dip, and rake of the fault plane. The model permits a relatively straightforward means of translating a suite of seismic source parameters to earth surface deformation for tsunami generation.

5.4. Post-processing

Post processing consists of translating the rates associated with a suite of source earthquakes to rates associated with their inundation. The probability of tsunami inundation at any particular spot along a coastline follows a Poisson model of recurrence (González et al. 2009). For a suite of tsunami inundation scenarios, the joint probability of inundation from the events, therefore, is the sum of the individual probabilities. In mathematical terms, the Poissonian, time-independent probability that a certain location will be inundated due to an occurrence of a tsunami during a time period T is
\[ P_{ij}(\zeta > \zeta_i) = 1 - e^{-\mu_j T}, \quad (15) \]

where \( P_{ij} \) is the probability that a specific level, \( \zeta_i \), will be exceeded by \( \zeta \) due to the occurrence of the \( j^{th} \) tsunami source. The joint probability of inundation can be expressed as the product of the individual probabilities:

\[ P_i(\zeta > \zeta_i) = 1 - \prod_j (1 - P_{ij}) = 1 - \prod_j e^{-\mu_j T} = 1 - e^{-\mu_j T} \quad (16) \]

so that the cumulative recurrence rate is the sum of the individual recurrence rates:

\[ \mu = \sum_j \mu_j \quad (17) \]

For example, if a specific grid cell on the coast is inundated by three events in a suite of tsunamis and their annual probabilities of occurrence are all 1/1000 per yr, the recurrence interval for inundation at that site is 1000/3 yrs, or 333 yrs, which corresponds to an AEP of 1/333. Repetition of these simple calculations at all grid cells produces a map of AEP over the site. AEP inundation limits are calculated from the grid utilizing any number of raster contouring tools, which in this case produces the 1/100 and 1/500 AEP inundation limits utilized in this project.
Chapter 6

Results and Discussion

A thorough seismic analysis with a suite of possible regional and circum-Pacific earthquakes and their recurrence rates combined with NEOWAVE provides the foundation for conducting PTHA of American Samoa. One of the primary advantages to the approach proposed in this analysis, namely conducting a complete analysis initially using the computationally cheaper hydrostatic switch in NEOWAVE, is that a number of the candidate runs can be excluded from a future non-hydrostatic PTHA of the entire island territory. The approach also provides a relatively cheap means of conducting sensitivity analyses to various source regions.

6.1. Regional Events

A total of 195 model runs are used for the near-field probabilistic calculations: 22 Mw 9+, 12 each of Mw 8.5-8.9 in 0.1 Mw increments, 18 Mw 8.4, 4 Mw 8.1, 20 Mw 8.0, 20 each of Mw 7.9 and 7.8, 10 each of Mw 7.7, 7.6, and 7.5, and 1 Mw 7.3. The elapsed time for all of the runs was 5 hrs. They take from two to five days to complete depending on the grid size. Once the model runs are complete, different scenarios for probabilistic inundation can be quickly assembled and compared.

Figure 12 shows a plot of the 1/100 and 1/500 AEP tsunami inundation limits and the flow depth contours from the modeled 2009 Samoa tsunami for comparison in the level-4 grid. The black line represents the 1/100 AEP limit and the red line represents the 1/500 AEP limit. The 1/100 AEP limit corresponds well with the inundation seen from the 2009 tsunami. There are several notable locations where the two limits diverge, however. In Pago Pago, the 1/100 AEP limit overestimates the inundation the inundation seen in 2009 event. At Aua, however, the inundation limit and the 1/100 AEP limit are coincident. On either side of the entrance to the harbor, at both Lauli’i and Matu’i, the inundation limit of the 2009 event exceeds the 1/100 AEP limit and is, in fact, coincident with the 1/500 AEP limit. For most other locations in the modeling domain, however, the 1/100 AEP limit represents the 2009 inundation limit well.
Figure 13 shows the 1/100 AEP limit compared to a Type I event (characteristic Mw 9.0) on the northern corner of the trench. The Type I inundation is very similar to the 2009 event. The 2009 event came from a Mw 8.1, so less inundation might be expected than for a Mw 9.0 earthquake. However, the slip associated with the 2009 event varies from 5.44 m to 16.5 m. The maximum slip for the Type I event is only 8.5 m. Although the magnitude of an earthquake is directly proportional to slip, a smaller magnitude earthquake can have more slip than a larger earthquake depending on the fault dimensions. The slip appears to play a larger role in observed tsunami run-ups and inundations than the magnitude by itself. Figures 14 and 15 show the inundation from Type III (characteristic Mw 9.2) and Type IV (characteristic Mw 9.1) events on the northern corner of the trench, respectively, compared to the AEP inundation limits. The moment magnitude of the Type III event is greater than the moment magnitude of the Type IV event, so the inundation might be expected to be more severe for the Type III event. The slip of the Type IV event is greater than for the Type III event, and that leads to larger modeled run-ups and more extensive inundation for the Type IV event than the Type III event. Again, slip plays an important part in tsunami inundation. Figures 16 and 17 show the inundation for the Type II (characteristic Mw 9.5) and Type V (characteristic Mw 9.3) events on the northern corner of the trench compared to the AEP inundation limits. The slips for the Type II and V events are 35 m and 10 m, respectively. Again, the inundation caused from a higher slipping event is greater than for a smaller slipping event.

Figure 18 shows the inundation from a Mw 8.9 event on the northern portion of the trench with uniform slip of 15.19 m and a fault length of 500 km. The event roughly corresponds to the 1/500 AEP inundation limit. Figures 19 and 20 show Mw 8.9 events with 2:1 - deep:shallow and 1:2 – deep:shallow slip distributions, respectively; their average slip distributions are the same as the Mw 8.9 event with a uniform slip of 15.19 m. The comparison highlights the impact of earthquake depth on inundation, and provides further support to the notion that slip plays a large role in tsunami run-up. The inundation for the 1:2 – deep:shallow slip distribution is the greatest amongst the three configurations of slip distribution. When the slip is greatest in shallow faulting earthquakes, the corresponding tsunamis show greater inundation.
Figures 21-23 show the inundation from Mw 8.0, 8.1, and 8.4 events on the northern portion of the Tonga Trench nearest to American Samoa, respectively. The Mw 8.0 event is negligible compared to the 1/100 AEP limit. The maximum slip associated with any of the Mw 8.0 runs is only 3.4 m (with a length of 150 km and a width of 50 km), which largely explains why its inundation is so small. The maximum flow-depth from the Mw 8.0 event is 2.8 m, and the only location in the modeling domain where the flow-depth exceeds 2 m is a headland at Brakers Point near Laulii, which is likely due to local amplification on steep bathymetry. The Mw 8.1 event, which is an outer-rise event pointing directly at American Samoa, corresponds roughly to the 1/500 AEP limit. The Mw 8.1 events produce the greatest inundation of any of the events from the Mw 8.0-8.4 group. Again, this can be attributed to a shallow, relatively large slip of 15 m (Lay et al. 2010). Unlike the modeled 2009 event, which was calibrated against the observed wave form seen at the Pago Pago tide gauge during the event, the 2009 events used for the probabilistic calculations were based solely on the work of Lay et al. (2010). The discrepancy between the two modeled events, although they represent the same event, can be attributed to different values used for the dip angle. The dip angle used in the calibrated 2009 model run varies from 20° to 35°, whereas the dip angle used in the probabilistic 2009 runs is 65°, meaning that a greater proportion of the slip for the probabilistic runs translates to vertical seafloor movement, which in turn results in waves with larger amplitudes. The Mw 8.4 inundation limit falls a little short of the 1/100 AEP limit in most places. There are a few locations where the worst-case Mw 8.4 inundation meets the 1/100 AEP inundation limit, in which case it influences the 1/100 limit. The Mw 8.4 events serve to fill in the lower recurrence intervals, intervals on the order of 50 yrs.

6.2. Pacific Rim Events

Table 9 shows the recurrence intervals per event per subduction zone for Mw 9+ Pacific Rim events. All modeled events were based on the “average” Mw 9+ historic event, using average fault widths, lengths, and slips as well as an assumed magnitude of Mw 9.26, length of 700 km, width of 200 km, and uniform slip of 28.3 m. Forty five Pacific Rim events were modeled across the nine subduction zones. Of the 45 events,
only three events result in inundation that exceeds the 1/100 AEP inundation limit for the Tonga Trench: one from Kamchatka, one from Central America, and one from South Chile, all three of which are compared to the AEP limits shown in Figures 24-26, respectively. The inundation from the South Chile event barely exceeds the 1/100 AEP limit. Constraining the occurrence of such events to specific parts of a trench reduces their recurrence intervals substantially. The recurrence interval for a single event in South Chile, as can be seen in Table 9, is very high, almost 10,000 yrs, so it will have no influence on the AEP limits. Likewise, the recurrence intervals for the worst-case Central American and Kamchatka events are too high to influence the AEP limits. Therefore, the Mw 9+ Pacific Rim events can be neglected in the PTHA of American Samoa.

6.3. Probabilistic Maps

The ultimate goal of the project is to produce an extensible and flexible method for conducting a PTHA of American Samoa. The task is computationally expensive, so any decrease in the number of model runs is useful in developing hazard maps in a reasonable timeframe. Several scenarios are explored to determine which events can be excluded from the analysis to produce the same 1/100 and 1/500 AEP limits as the full suite of 195 events.

Figure 27 shows a map of the 1/100 and 1/500 AEP inundation limits that incorporates all regional events in the analysis. Some of the regional events, however, can be excluded from the analysis based upon their inundations. In particular, as can be seen in Figure 21, the Mw 8.0 events result in inundation that falls well short of the 1/100 AEP inundation limit. They can be excluded from the analysis. Figure 28 shows the AEP limits compared to the worst-case Mw 7.9 earthquake. The modeled inundation, like the Mw 8.0 event, falls short of the 1/100 AEP limit, which means that all events whose magnitudes are less than 8.0 can be excluded from the analysis. Furthermore, events sourced from the Kermadec portion of the regional subduction system (south of the Louisville Ridge) exhibit little inundation and have a marginal impact on the 1/100 and 1/500 AEP inundation limits, and they can be excluded from the analysis.

Figure 29 shows a map of the AEP limits for all modeled events and for all modeled events excluding Mw <= 8.0 and Kermadec events. There is almost no
difference with the results in Figure 28 that include all the modeled events. The only noticeable difference is around Matu’u, which is likely due to terracing of the land and flooding in the model runs. Excluding Mw <= 8.0 and the Kermadec events culls the number of model runs needed for a PTHA of American Samoa from 195 to 93. The events excluded include 11 Kermadec runs, 20 Mw 8.0 runs, 70 Mw 7.5-7.9 runs, and one Mw 7.3 run, a decrease of 50% in the number of model runs. With a suite of suitable earthquakes to model and the resulting AEP limits, the limits need to be compared to other events to determine the efficacy of the approach used in this study.

The 1/100 AEP limit corresponds well with the 2009 event. The 1/500 AEP limit, however, is more difficult to assign a known event since no historical events have produced inundation coincident with the 1/500 AEP limit. There is paleotsunami evidence that an event occurred about 500 yrs BP that impacted all of the PICs. Unlike the 1/100 AEP event, whose proxies for recurrence are the 1917 and 2009 Samoa events, the actual run-up and inundation in American Samoa for the proposed 1/500 AEP event is difficult to constrain; there are no published studies that have been able to constrain the magnitude of local run-up or inundation of the event 500 yrs BP in American Samoa.

A study by Goff et al. (2010) identifies three large tsunamis in New Zealand in Kaituna Bay – ~550 yrs BP, ~2800 yrs BP, and ~6500 yrs BP, with local run-ups inferred from dune deposits at an elevation of ~32 m. Assuming that all three events represent a similarly sized tsunami, the recurrence interval for such an event is 2000 yrs. Location and orientation of an earthquake on the Tonga Trench have the greatest effect on tsunami run-up in American Samoa. Assuming that the same applies to New Zealand, the source of an earthquake to produce run-ups on the order of the 1450 event would have to be in the southern Kermadec Trench, which has a convergence rate of ~6 cm/yr. The convergence rate of the north Tonga Trench is ~24 cm/yr. Scaling the two against each other, the inferred recurrence interval for an event like the 1450 New Zealand event for the North Tonga Trench is 2000 x 6/24 = 500 yrs. The maximum run-up associated with the 1/500 AEP event for Pago Pago is only ~20 m. Other parts of Tutuila, especially the West Side, likely have run-ups similar to the New Zealand event. More paleotsunami work needs to be conducted to more tightly constrain the run-up associated with a 1/500 AEP tsunami.
Tsunami hazard analyses provide telling insights into the nature of tsunami inundation. Site specific inundation proves to be very sensitive to fault direction relative to the site – Mw 9+ earthquakes on the Kermadec Trench have almost no impact on the 1/100 AEP inundation limit because the direction of the energy propagation points away from American Samoa. Many of the runs could have been excluded from the analysis by evaluating their trench normal directions relative to American Samoa, which would have conserved CPU time. In addition to the regional events, the Pacific Rim analysis provided insights into the hazard posed by tele-tsunamis. Although they pose less threat than their regional brethren, far-field tsunamis can be devastating, especially from a few specific locations, which have been identified in the analysis. In the event of a Mw 9+ earthquake on one of the three locations identified around the Pacific that produces tsunamis that exceed the 1/100 AEP limit, the population could be evacuated beyond the 1/500 AEP inundation limit; the same goes for the events sourced from regions that produce events that approach but do not exceed 1/100 AEP limit. Many of the events sourced from Chile, although none of them exceed the 1/100 AEP limit, approach the limit, more than any other Pacific Rim source. If a great earthquake occurs on the Chile Trench, the best course of action would be to evacuate the population beyond the 1/100 AEP limit.
Chapter 7

Conclusions and Future Work

The work presented in this study provides a compact framework for a PTHA of America Samoa. The framework can be applied to the other seven modeling sub-domains for American Samoa for a fully non-hydrostatic PTHA of American Samoa. The resulting maps can be used to develop multi-tiered evacuation maps for the island territory, the need for which is highlighted by the occurrence of the 2004 Sumatra, 2009 Samoa, and 2011 Tohoku tsunamis. The methodology used to develop the framework, namely apportioning the probability that a Mw 9+ earthquake will occur on a specific subduction zone by the convergence rate, length, and obliquity of convergence, can be applied to other regions around the world, too. The use of hydrostatic model runs provides an effective first-order estimation of tsunami hazard, while the non-hydrostatic runs provide a basis for the development of multi-tiered tsunami evacuation maps.

In addition to a first-order near-field assessment of tsunami hazard, the run-up and inundation from circum-Pacific sources evaluated in this study can provide a basis for a general tsunami hazard analysis of American Samoa. Specific source regions can be identified that pose more risk to American Samoa than others. Consequently, in the event of a large circum-Pacific event, the source location can be used as a means of determining the likely severity of a resultant tsunami in American Samoa.

A couple of uncertainties were either neglected or incorporated as a worst-case scenario, both of which are aleatory and could be incorporated with the addition of a few bifurcations to the logic trees. The tides in American Samoa, although the range is not particularly large (0.828 m), are semi-diurnal and may play a complex role in tsunami run-up, especially considering the presence of a shallow fringing reef. During low tide, the depth of the water over the reef is much shallower than during high tide, which may have a substantial impact on tsunami run-up. To account for this, two branches could be added to the logic trees for MSL and MLLW.

The addition of aleatory uncertainty for tides increases the number of events needed for the hazard analysis by a factor of three, not something to take lightly when
considering which events to include in a fully non-hydrostatic analysis. The number of candidate runs has been winnowed down to 93 from the original 195. The addition of branches in the logic tree for tides would bring the number up to 279, an expensive computational cost.

Another aleatory uncertainty is the potential for the occurrence of a storm during the tsunami. A large tropical storm can raise the water level by meters, which could have devastating effects if a tsunami made landfall concomitantly. However, the joint probability of a storm and a great tsunami occurring at the same time puts the AEP in the thousands. For example, assuming the rate of large tropical storms is 1/10 and the rate of large tsunamis is 1/500, the joint rate is 1/5000. A branch to the logic trees could be added to account for storms with the weight of the branch a function of the likelihood that a storm occurs at any particular time (the other branch weighted by the probability that a storm is not occurring during a tsunami), but the return periods are so high that they would not influence the 1/100 or 1/500 AEP limits.

A useful tool that may, in the future, help constrain the magnitude of a 500 yr event (and provide more data points for the 100 yr event) on American Samoa is inverse tsunami modeling (Jaffé and Gelfenbaum 2007, Moore et al. 2007, Apotsos et al. 2011, Jaffé et al. 2011). The inverse problem looks to resolve tsunami flow speeds from variations in tsunami deposits. Different flow speeds produce different settling characteristics, from which inverse modeling can deduce the tsunami that produced the deposits. Once the source tsunami is known, the run-up and inundation can be modeled, which puts a constraint on an event with a known recurrence interval. Further work in American Samoa could be conducted to help constrain tsunami recurrence intervals based on Paleotsunami deposits.

The work presented in this study lays the groundwork for a fully non-hydrostatic tsunami hazard assessment of American Samoa. Both near-field and far-field sources are incorporated while maintaining the minimum number of model runs needed to adequately capture tsunami run-up and inundation statics for the territory. If recurrence intervals less than 100 yrs are not needed and storms and tides are not included in the logic trees, the total number of runs needed per sub-domain is 93. There are eight sub-domains, so 8 x 93
= 744 runs are needed to conduct a full hazard analysis of American Samoa. The difficulty of building a framework that incorporates enough variation to capture the uncertainty of a system while minimizing model run time becomes apparent when considering that it takes about a week to run a single near-field event, so the above analysis would take about 744 weeks (or 14.3 yrs) on a single core. If 64 cores are used continuously, however, that number decreases to 11.6 weeks, which is still significant.
Table 1: Mw 9+ Earthquake Fault Characteristics (Butler 2014)

<table>
<thead>
<tr>
<th>Earthquake &amp; Date</th>
<th>Moment $10^{22}$ N-m</th>
<th>Mw</th>
<th>Length km</th>
<th>Width km</th>
<th>Average Slip m</th>
<th>Peak Slip m</th>
<th>Citations</th>
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<td>Kamchatka 11/4/1952</td>
<td>23.7</td>
<td>8.85</td>
<td>500</td>
<td>100-200</td>
<td>7.7</td>
<td>11.4$^b$</td>
<td>Johnson and Satake 1999</td>
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<tr>
<td>Kamchatka 23$^1$</td>
<td>8.84</td>
<td>600$^2$</td>
<td>150$^2$</td>
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<td></td>
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<tr>
<td>Chile 5/22/1960</td>
<td>270$^*$</td>
<td>9.55</td>
<td>800$^*$</td>
<td>200$^*$</td>
<td>38</td>
<td></td>
<td>Kanamori and Cipar 1974</td>
</tr>
<tr>
<td>Chile 320</td>
<td>9.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cifuentes 1989</td>
</tr>
<tr>
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<td>9.14</td>
<td>900</td>
<td>150</td>
<td>11</td>
<td>30±10</td>
<td></td>
<td>Fuji and Satake 2012</td>
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<td>150</td>
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<td>41</td>
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<td>1000</td>
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<td>200-300</td>
<td>8.6</td>
<td>22</td>
<td></td>
<td>Johnson et al. 1996</td>
</tr>
<tr>
<td>Alaska 55</td>
<td>9.1</td>
<td>740</td>
<td>250-300</td>
<td>4.9</td>
<td>17.4</td>
<td></td>
<td>Ichinose et al.</td>
</tr>
<tr>
<td>Type</td>
<td>Fault Length (km)</td>
<td>Average Slip (m)</td>
<td>Reference</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------</td>
<td>------------------</td>
<td>-----------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| I. Largest slip down-dip from trench 1952 Kamchatka | 600               |                  | Uniform across length:  
|                           |                   |                  | - Shallow: 1.5  
|                           |                   |                  | - Deep: 8.5 |
| Sumatra 2007              |                   |                  | Ammon et al. 2005 |
| 12/26/2004                |                   |                  | Lay et al. 2005  |
|                           |                   |                  | Tsai et al. 2005 |
|                           |                   |                  | Stein and Okal 2007 |
| Tohoku 2011               |                   |                  | Nettles et al. 2011 |
| 3/11/2011                 | 350              | 150              | >50¹             |
|                           |                   |                  | Nettles et al. 2011, Simons et al. 2011 |
|                           | 43                | 450              | >25              |
|                           |                   |                  | Yoshida et al. 2011 |
|                           | 40                | 380              | 16               |
|                           |                   |                  | Lay et al. 2011 |
|                           | 48                | 440              | ~60              |
|                           |                   |                  | Yue and Lay 2011 |
|                           | 48                | 420-340          | 14               |
|                           |                   |                  | Yamazaki et al. 2011 |
|                           | 36                | 350              | 150              |
|                           |                   |                  | Ammon et al. 2011 |
|                           | 37                | ~400             | ~200             |
|                           |                   |                  | Lee et al. 2011  |
|                           | 42                | 400              | 16               |
|                           |                   |                  | Shao et al. 2011 |
|                           | 58                | 400              |                  |
|                           |                   |                  | Yokota et al. 2011 |

Table 2: Types of Mw 9+ Earthquakes
II. Large average slip  
1960 Chile  

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Slip</th>
<th>Rate of 9s from Paleotsunami Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960 Chile</td>
<td>700</td>
<td>35, uniform across depth and length</td>
</tr>
</tbody>
</table>

III. Two areas of large slip  
1964 Alaska  

- 700  
- In 100 km increments:  
  - Uniform across depth: 4, 14, 22, 4, 22, 14, 4

IV. Largest slip near trench  
2011 Tohoku  

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Slip</th>
<th>Rate of 9s from Paleotsunami Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 Tohoku</td>
<td>350</td>
<td>10, uniform across depth and length</td>
</tr>
</tbody>
</table>
- In 50 km increments:  
  - Shallow: 7, 16, 38, 53, 38, 16, 7  
  - Deep: 3, 9, 22, 24, 22, 9, 3

V. Very long fault rupture  
2004 Sumatra  

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Slip</th>
<th>Rate of 9s from Paleotsunami Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004 Sumatra</td>
<td>1400</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: b-values and Rates for the World and Select Locations

<table>
<thead>
<tr>
<th>Location</th>
<th>b-value</th>
<th>Rate of 7s</th>
<th>Rate of 8s</th>
<th>Rate of 9s</th>
<th>Rate of 9s from Paleotsunami Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>1.03</td>
<td>1/0.21</td>
<td>1/2.22</td>
<td>1/23.99</td>
<td>N/A</td>
</tr>
<tr>
<td>Tonga-Kermadec</td>
<td>0.79</td>
<td>1/3.77</td>
<td>1/23.07</td>
<td>1/141.25</td>
<td>1/600</td>
</tr>
<tr>
<td>Japan</td>
<td>1.07</td>
<td>1/0.94</td>
<td>1/11.04</td>
<td>1/129.36</td>
<td>1/1142</td>
</tr>
<tr>
<td>Sumatra-Andaman</td>
<td>0.87</td>
<td>1/3.14</td>
<td>1/23.35</td>
<td>1/173.7</td>
<td>1/500</td>
</tr>
<tr>
<td>Chile</td>
<td>0.76</td>
<td>1/1.64</td>
<td>1/9.39</td>
<td>1/53.89</td>
<td>1/500</td>
</tr>
<tr>
<td>Cascadia</td>
<td>1.25</td>
<td>1/113</td>
<td>1/2007</td>
<td>1/35,632</td>
<td>1/500</td>
</tr>
</tbody>
</table>

Table 4: Rates of Mw 9+ earthquakes for select locations based on the proportion of the world’s convergence rate

<table>
<thead>
<tr>
<th>Location</th>
<th>Gross-Net Convergence (%)</th>
<th>Gross-Net Rate of Mw 9+</th>
<th>Average Rate of Mw 9+</th>
<th>Rate of 9s from Paleotsunami Record</th>
</tr>
</thead>
<tbody>
<tr>
<td>Japan</td>
<td>1.9-2.2</td>
<td>1/1189-1/1027</td>
<td>1/1108</td>
<td>1/1142</td>
</tr>
<tr>
<td>Sumatra-Andaman</td>
<td>3.3-3.7</td>
<td>1/685-1/611</td>
<td>1/648</td>
<td>1/916</td>
</tr>
<tr>
<td>Chile</td>
<td>2.0-2.2</td>
<td>1/1130-1/1028</td>
<td>1/1079</td>
<td>1/500</td>
</tr>
<tr>
<td>Cascadia</td>
<td>1.5-1.5</td>
<td>1/1507-1/1507</td>
<td>1/1507</td>
<td>1/500</td>
</tr>
</tbody>
</table>
Table 5: Historic Mw 8+ Events on the Tonga Trench

<table>
<thead>
<tr>
<th>Year</th>
<th>Mw</th>
<th>Location</th>
<th>Mechanism</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1865</td>
<td>8.4</td>
<td>186.5°E, -20°N</td>
<td>thrust</td>
<td>Okal et al. 2004</td>
</tr>
<tr>
<td>20th Century</td>
<td>7.3</td>
<td>186°E, -15°N</td>
<td>STEP</td>
<td>Isacks et al 1969, Millen and Hamburger 1998</td>
</tr>
<tr>
<td>1917</td>
<td>8.0</td>
<td>187°E, -15.5°N</td>
<td>thrust</td>
<td>Okal et al. 2011</td>
</tr>
<tr>
<td>1919</td>
<td>8.1</td>
<td>187.5°E, -19°N</td>
<td>outer rise</td>
<td>Okal et al. 2011</td>
</tr>
<tr>
<td>2009</td>
<td>8.1</td>
<td>188°E, -15.5°N</td>
<td>outer rise</td>
<td>Beaven et al. 2010, Lay et al. 2010</td>
</tr>
<tr>
<td>2009</td>
<td>8.0</td>
<td>187.5°E, -16.2°N</td>
<td>thrust</td>
<td>Lay et al. 2010</td>
</tr>
</tbody>
</table>

Table 6: Scaled Recurrence Rates for Mw 7.5 – 7.9 for the North Tonga Trench in Mw 0.1 Bins

<table>
<thead>
<tr>
<th>Mw</th>
<th>Recurrence Rate (per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>1/67.67</td>
</tr>
<tr>
<td>7.6</td>
<td>1/85.86</td>
</tr>
<tr>
<td>7.7</td>
<td>1/108.94</td>
</tr>
<tr>
<td>7.8</td>
<td>1/138.23</td>
</tr>
<tr>
<td>7.9</td>
<td>1/175.39</td>
</tr>
<tr>
<td>8.0</td>
<td>1/385.38</td>
</tr>
<tr>
<td>8.1</td>
<td>1/488.99</td>
</tr>
<tr>
<td>8.2</td>
<td>1/620.45</td>
</tr>
<tr>
<td>8.3</td>
<td>1/787.26</td>
</tr>
<tr>
<td>8.4</td>
<td>1/998.91</td>
</tr>
</tbody>
</table>

Table 7: Nested Grids used in NEOWAVE

<table>
<thead>
<tr>
<th>Grid level</th>
<th>resolution</th>
<th>Longitude Range</th>
<th>Latitude Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonga Trench</td>
<td>2.0 arc-minutes</td>
<td>variable</td>
<td>variable</td>
</tr>
<tr>
<td>American Samoa</td>
<td>30.0 arc-seconds</td>
<td>variable</td>
<td>variable</td>
</tr>
<tr>
<td>Tutuila</td>
<td>3.0 arc-seconds</td>
<td>188.9°E to -14.5°N</td>
<td>14.1°N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>189.7°E to -14.305°N</td>
<td>-14.265°N</td>
</tr>
<tr>
<td>Pago Pago</td>
<td>0.3 arc-seconds</td>
<td>189.345°E to -14.29°E</td>
<td>-14.1°N</td>
</tr>
</tbody>
</table>

Table 8: Bathymetry and Topography Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>Data Type</th>
<th>Coverage Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Bathymetric Chart of the Oceans (GEBCO) - <a href="http://www.gebco.net/">http://www.gebco.net/</a></td>
<td>30 arc-second</td>
<td>Worldwide</td>
</tr>
</tbody>
</table>
Pacific Islands Benthic Habitat Mapping Center (PIBHMC) - http://www.soest.hawaii.edu/pibhmc/


National Oceanic and Atmospheric Administration (NOAA) LiDAR http://www.csc.noaa.gov/dataviewer/#app=f8ce&6ba3-selectedIndex=1

<table>
<thead>
<tr>
<th>Subduction Zone</th>
<th>Recurrence Interval for the Subduction Zone</th>
<th>Number of Modeled Events that Exceed the Regional 1/100 AEP Limit</th>
<th>Recurrence Interval for Events that Exceed the Regional 1/100 AEP Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Chile</td>
<td>4570</td>
<td>1</td>
<td>9141</td>
</tr>
<tr>
<td>Chile</td>
<td>174</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Ecuador</td>
<td>706</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Central America</td>
<td>312</td>
<td>1</td>
<td>1332</td>
</tr>
<tr>
<td>Alaska-Aleutian</td>
<td>253</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Kamchatka</td>
<td>181</td>
<td>1</td>
<td>1131</td>
</tr>
<tr>
<td>Ryukyu</td>
<td>378</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>The Philippines</td>
<td>432</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Vanuatu</td>
<td>243</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Figure 1: Historic Earthquakes and Modified SIFT Unit Faults, outer rise faults, and a STEP Fault on the Tonga-Kermadec Trench.
Figure 2: Circum-Pacific Historic Earthquakes and SIFT Unit Faults

Figure 3: Cumulative Worldwide Seismic Moment Release for all Earthquakes, Mw 7.0-10.0 and Mw 7.0-8.9, and for Subduction Zone Earthquakes, Mw 7.0-10.0 and Mw 7.0-8.9
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Figure 5: Logic Tree for Mw 8.0 Thrust Faulting Earthquakes on the Tonga-Kermadec Trench
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Figure 11: Okada (1985) Planar Fault Model
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Figure 13: 1/100 and 1/500 AEP Limits and the Type I Event Nearest to American Samoa
Figure 14: 1/100 and 1/500 AEP Lines and the Type III Event Nearest to American Samoa

Figure 15: 1/100 and 1/500 AEP Lines and the Type IV Event Nearest to American Samoa
Figure 16: 1/100 and 1/500 AEP Lines and the Type II Event Nearest to American Samoa

Figure 17: 1/100 and 1/500 AEP Lines and the Type V Event Nearest to American Samoa
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Figure 19: 1/100 and 1/500 AEP Lines and a Mw 8.9 Earthquake with 2:1 – deep:shallow Slip Distribution Nearest to American Samoa
Figure 20: 1/100 and 1/500 AEP Lines and a Mw 8.9 Earthquake with 2:1 – shallow:deep Slip Distribution Nearest to American Samoa

Figure 21: 1/100 and 1/500 AEP Lines and a Mw 8.0 Earthquake Nearest to American Samoa
Figure 22: 1/100 and 1/500 AEP Lines and a Mw 8.1 Earthquake Nearest to American Samoa

Figure 23: 1/100 and 1/500 AEP Lines and a Mw 8.4 Earthquake Nearest to American Samoa
Figure 24: 1/100 and 1/500 AEP Lines and the only Kamchatka Event whose Inundation exceeds the 1/100 AEP limit

Figure 25: 1/100 and 1/500 AEP Lines and the only Central American Event whose Inundation exceeds the 1/100 AEP limit
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Figure 28: 1/100 and 1/500 AEP Lines and a Mw 7.9 Earthquake Nearest to American Samoa with Uniform Slip, $L = 100$ km, and $W = 50$ km

Figure 29: 1/100 and 1/500 AEP Limits – All Regional Events Compared to Mw 7.3-8.0 Removed from Analysis
Bibliography


Oliver, J. and Isacks, B. (1967). Deep Earthquake Zones, Anomalous Structures in the


