Field Observations and Modeling of Tsunamis on the Islands of the Four Mountains, Aleutian Islands, Alaska

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Introduction

Adequate geophysical and historical information for assessing the potential danger of earthquakes and accurately predicting patterns of rupture do not exist for the Aleutian subduction zone. The historical records and eyewitness accounts are sparse, and the paleotsunami record is unstudied. To accurately assess the tsunami hazard facing countries throughout the Pacific Ocean because of the Aleutian subduction zone, the seismic history of the arc needs to be better documented and quantified. To document the frequency and magnitude of tsunamis along the Aleutian subduction zone, particularly near the Islands of the Four Mountains (IFM), I will identify paleotsunami, the 1946 tsunami, and the 1957 tsunami deposits in the field. I will then model these events using GeoClaw, a two-dimensional, shallow wave, open-source software package to determine the magnitude of earthquakes that can produce the identified tsunami deposits. By combining field and modeling components I will produce first-order estimates of how often and how large past earthquakes and subsequent tsunamis were along the eastern segment of the Aleutian subduction zone, specifically in the vicinity of IFM. The eastern Aleutians is an important place to conduct paleotsunami studies because the directionality of the eastern segment of the subduction zone, that is the direction of tsunami propagation, poses a great threat to countries across the Pacific and the west coast of the continental U.S. in particular.

Background Information

The Aleutian Islands are a volcanic arc located between the Pacific Ocean and the Bering Sea where the Pacific Plate is subducting beneath the Bering Plate at a rate of 66 mm/yr in the eastern and central Aleutians (Cross and Freymueller, 2008) (Figure 1). In the western Aleutians, west of the Amchitka pass, relative plate motion transitions to strike-slip motion.

The IFM are located in the eastern section of the Aleutian Islands and consists of six volcanoes: Herbert, Cleveland, Tana, Kagamil, Uliaga, and Carlisle. Two of these volcanoes, Cleveland and Carlisle, are active today. While Cleveland is one of the most active in the Aleutians arc, it is not monitored at this time (USGS, AVO). IFM is bounded on either side by two deep, open water passes that separate IFM from the Fox Islands to the east and the Andreanof Islands to the west.

Asperity models in the Aleutian Islands indicate three seismic gaps, two of which are in the eastern Aleutians (Figure 2). Seismic gaps are areas on a fault that are known to have large rupture events but have not ruptured in recent history. Seismic gaps are thought to be locations where large ruptures will occur next. An asperity is a coupled section of a fault that is of higher strength and stress compared to surrounding areas, and it is these areas that initiate rupture and cause an earthquake (Jean M Johnson, 1997). Lay and Kanamori (2008) proposed that the eastern Aleutians do not have concentrated asperities because ruptures occur as large events with rupture zones of several hundred kilometers, rather than in smaller sections or blocks. The western Aleutians, near the Rat Islands, exhibit smaller asperities located on tectonic blocks (Johnson et al., 1996). Asperities in the central and western portions of the subduction zone rupture with variable rupture cycle (Jean M Johnson, 1997).

There have been five major earthquakes along the Aleutian arc in the past century. Figure 2 shows the rupture areas of the five largest earthquakes (Mw > 7.5) and other significant but smaller magnitude ruptures between 1900-2004 While my research will focus on the eastern portion of the Aleutian arc, documenting the rupture history of the entire arc is important for a comprehensive representation of subduction, and my research will contribute to this larger study. The large ruptures are the 1938 Alaskan, 1946 Aleutian, 1957 Aleutian, 1964 Prince William Sound, and the 1965 Rat Islands earthquakes (Jean M Johnson, 1997). These five events ruptured nearly the entire length of the Aleutian arc, excluding three seismic gaps, which have not ruptured in recorded history.

The Islands of the Four Mountains is a good place to conduct this study for several reasons:

(1) The IFM and vicinity is located within an area of large moment release in the 1957 event. The 1957 earthquake was associated with a large slip in the western portion of the aftershock zone, with no significant slip in the east except for near IFM (Johnson and Satake, 1994) (Figure 3).

(2) Recent work done by a USGS team found well-preserved evidence of the 1957 tsunami in Driftwood Bay on Unmak, a neighboring island to the west. Their work would provide the opportunity to extend my study area to the west, and it also indicates that IFM may also have clear evidence of the 1957 event (Rob Witter, personal communication 2013). Additionally, while the bathymetry is not yet refined to a resolution that would indicate whether or not tsunamis would be amplified near IFM, the islands sit in the middle of a deep-water pass, so amplification is possible, which would add to the probability of preserved deposits.

(3) The cost of visiting any Aleutian island is considerable, however an ongoing NSF project conducting an archeological study will provide my transportation to the IFM. In turn, I will provide both field observations and modeling data of the possible impact of tsunamis at the archeological sites.

(4) The large historical events that should have affected IFM (1957 and possibly 1946) are old enough for deposits to be preserved similar to paleotsunami deposits, while recent enough that these deposits should be identified easily. Studying these large historical events will provide an excellent basis for comparing the inundation extent of paleotsunami events to historical events.

(5) Several active volcanoes on IFM are the source for local tephra layers, which are critical for determining how many tsunamis, occurred from paleotsunami deposits. Figure 4 shows the locations of these volcanoes with the locations of where we will conduct tsunami surveys during fieldwork.

There have been few paleotsunami studies conducted in the Aleutian Islands, and even historical earthquakes were not adequately recorded. Most of the large earthquakes in the past century along the Aleutian subduction zone were poorly documented because not only is the historical record sparse for Aleutian events due to low populations, but the World Wide Standard Seismograph Network (WWSSN) was not installed until the 1960's, later than many of the historical events, resulting in incomplete records of historical earthquake parameters. In order to determine the parameters of previous earthquake and the locations of asperities, tsunami waveforms and deposits are crucial.

Methods and Logistics

In this project, I will combine fieldwork and tsunami modeling to determine rupture characteristics of earthquakes that could reasonably produce historical and paleotsunami deposits seen in the eastern Aleutian field site of the IFM. Field methods, including trenching to create correlated stratigraphic columns and mapping the lateral extent of tsunami deposits, will be after the work of Pinegina et al., 2003 and MacInnes et al., 2010. These field methods will allow me to discover and identify tsunami deposits, paleotsunami deposits, and tephra layers.

The primary goal of field investigations will be to find and accurately identify paleotsunami deposits. Tsunami deposits are layers of sand that fine and thin inland, following topography (Dawson and Shi, 2000). Deposit extent indicates the minimum inundation distance of the tsunami and deposits are most likely to be found where the tsunami went over dunes or ridges (Synolakis et al., 1999). Inundation distances of tsunami deposits can be compared to estimate the relative size and extent of the tsunamis. Inundation distance is a measure of how far inland a tsunami deposit extends and is a minimum estimate of the inland extent of the water during the tsunami (MacInnes et al., 2010). I will also identify tsunami deposits and geomorphic indicators of historical events from the 1957 earthquake, and potentially the 1946 earthquake, if present.

Paleotsunami deposits differ from tsunami deposits in that the paleotsunami event occurred before historical records, and therefore geologic information discovered in the field is all that is known about the event. Historical tsunami deposits have written records that can include information about the extent and size of the earthquake in addition to the geologic information found in the field. Coastal stratigraphy that includes historical and paleotsunami deposits with dated tephra allow one to calculate the recurrence interval of tsunami events. If funding allows I will conduct AMS radiocarbon dating of organic material in or stratigraphically near tsunami deposits to provide an absolute age of events (Minoura et al., 2005).

To determine the characteristics of rupture, I will model the tsunami deposits found in the field using GeoClaw. GeoClaw is a code that solves the two-dimensional, shallow-water wave equations using a finite volume method (LeVeque et al., 2011) to model tsunami propagation from seafloor deformation. It converts slip on a fault, or multiple faults, into instantaneous seafloor deformation based on the Okada 1985 equations. GeoClaw is an open source software package (LeVeque et al., 2011) that is approved by the United States National Tsunami Program for the modeling of tsunamis (Gonzalez, 2012). GeoClaw employs an adaptive mesh refinement (AMR), which increases resolution near the wave front of the modeled tsunami, allowing for finer resolution in coastal areas of interest.

In order to obtain better accuracy in results from GeoClaw, the bathymetry near IFM needs to be refined to have resolution close to 10-50 m. Using ArcGIS, I will create a grid of finer resolution bathymetry around IFM and Unmak, AK by combining ETOPO base maps, global relief model that integrates land topography and ocean bathymetry generated by NOAA that have a resolution of 1 arc-minute (100-500 m), and NOAA nautical bathymetry charts (NOAA). This will allow for the higher resolution AMR to be overlaid in GeoClaw in order to have a more detailed model of inundation inland and wave interaction with bathymetry.

Anticipated Results and Benefits

Recent work conducted by the USGS indicates that on Unmak Island, the islands directly to the east of IFM, there are 1957 tsunami deposits of up to 23 meters in Driftwood Bay (Rob Witter, personal communication 2013). Because distinct wracklines have been observed near IFM, I anticipate finding deposits of the 1957 event on IFM. Google Earth shows an embayment on IFM, where 1957 deposits were discovered (Figure 4).

Our preliminary model of the 1957 earthquake and tsunami based on the source model of Johnson et al. (1994) produced a tsunami wave of 1 meter. This does not agree with the 23-m high observations in Driftwood Bay on Unmak, indicating the earthquake parameters of the source model presented by (Johnson and Satake, 1994) need to be modified. Part of the discrepancy between the model and field observations could be inaccurate bathymetry or amplifications in Driftwood Bay that does not correlate to IFM, however, a 1:23 amplification or 22-m difference due to bathymetric inaccuracy is highly unlikely.

This project will contribute to understanding the mechanisms and pattern of rupture along the Aleutian Island subduction zone by evaluating historical earthquakes and tsunamis and paleotsunamis in the Islands of the Four Mountains. The benefits of having a better history of rupture, including how often and how large of an event could occur, and knowing the temporal pattern in which these rupture events have occurred will enhance the ability to make accurate tsunami predictions for the eastern Aleutians. Because the directionality of the Aleutian subduction zone poses a great threat of tsunami across the Pacific Ocean, a better understanding of the mechanisms and pattern of rupture will help to better prepare coastal communities in the future.

Schedule

Winter 2014

Begin set up for preliminary modeling

Spring 2014

Present formal thesis proposal

Modeling of the 1957 event

Prepare for fieldwork

Summer 2014

Modeling of the hypothetical paleotsunami events

Go to Aleutian Islands for fieldwork (end July-mid August)

Conduct field studies and observations

Write thesis

Fall 2014

Process field observation data

Match modeling to field observations

Additional tsunami modeling based on field observations

Write thesis

Winter 2015

Write thesis

Spring 2015

Defend Thesis

Finish Revisions

<u>Budget</u>

Airfare, roundtrip from Seattle, WA to Dutch Harbor, AK -- $1200

Per Diem in Dutch Harbor (6 days; 3 pre-fieldwork, 3 post-fieldwork) -- $220/day x 6 days = $1,320

Per Diem on ship (20 days) -- $20/day x 20 days = $400

AMS Radiocarbon dating -- $350/sample x 5 samples = $1,750

<u>Justification for Budget</u>

The planned fieldwork entails twenty days on the Maritime Maid, a helicopter accessible ship that leaves from Dutch Harbor, AK. Airfare to and from Alaska is required in order to reach the boat. Food and lodging will be provided on the ship, which will anchor off the coast of IFM for the duration of the fieldwork, weather permitting. A few days are required prior to launch in Dutch Harbor in order to purchase, organize, and pack field supplies, food, and equipment. After returning from IFM a few days will be needed to process samples for shipment. Due to inclement weather a few days are added to account for possible delays. In Dutch Harbor, the Museum of the Aleutians will be a home base. AMS samples will be used to date charcoal or organic material to supplement the chronology provided through tephra dating.

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Figures

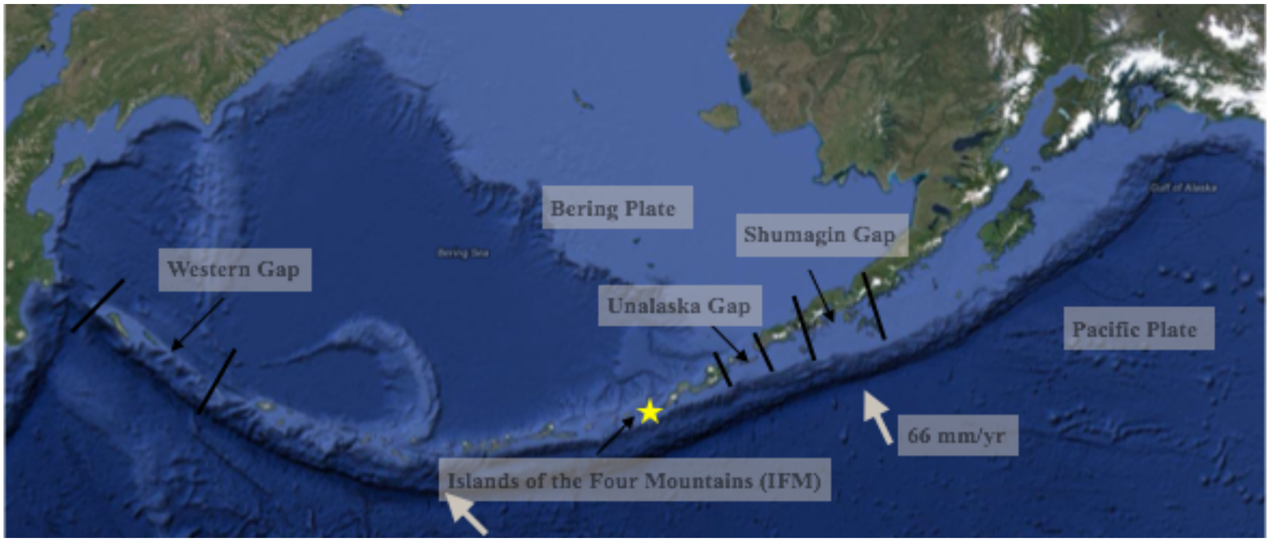

Figure 1: This map shows the geographic setting of Islands of the Four Mountains (IFM), indicated by the yellow star. The Pacific Plate is subducting beneath the Bering Plate in a northwester direction near the IFM (Cross and Feymueller, 2008). Three seismic gaps are located in the Aleutian Islands, indicating sections of the subduction zone known to have large ruptures, but which haven't ruptured in recent history.

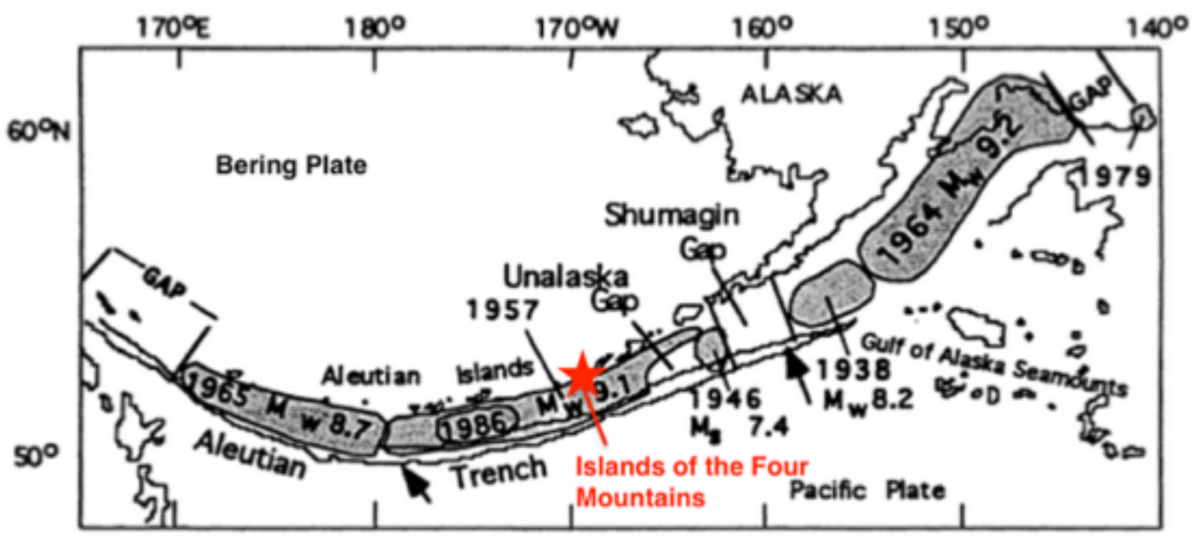

Figure 2:
Aftershock zones of historical tsunamigenic earthquakes. These seismic gaps are where there has not been a rupture in recorded history, but may be the location of a large future rupture. The Islands of the Four Mountains are located two islands east of the Unalaska Gap, indicated by the red star. (Figure modified from Johnson et al., 1994).

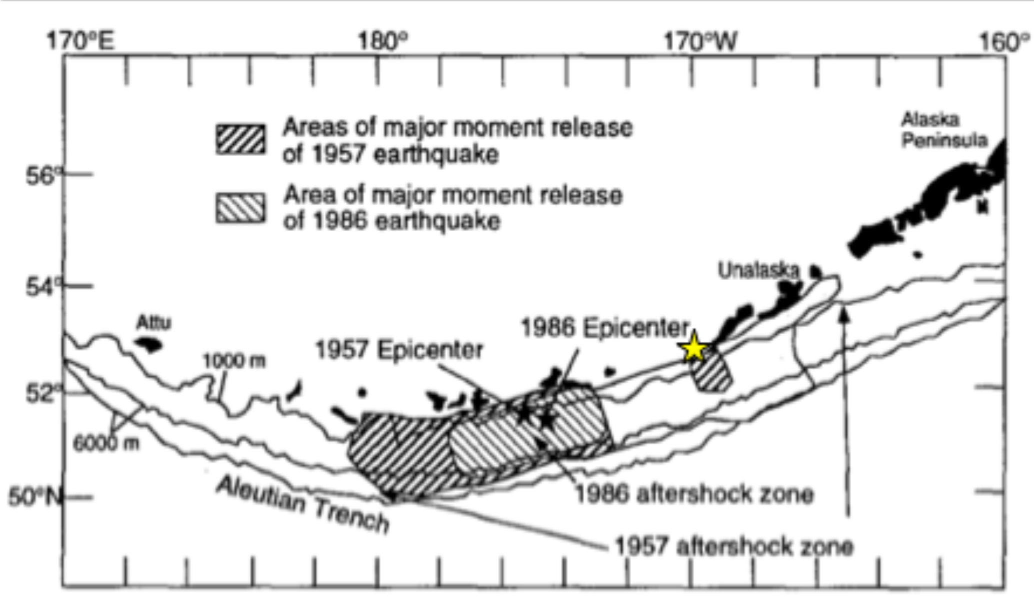

Figure 3:
Areas of large moment release of the 1957 Great Aleutian Earthquake and the 1986 Aleutian Earthquake. The IFM are located within an isolated area of large moment release during the 1957 event. (Johnson et al., 1994).

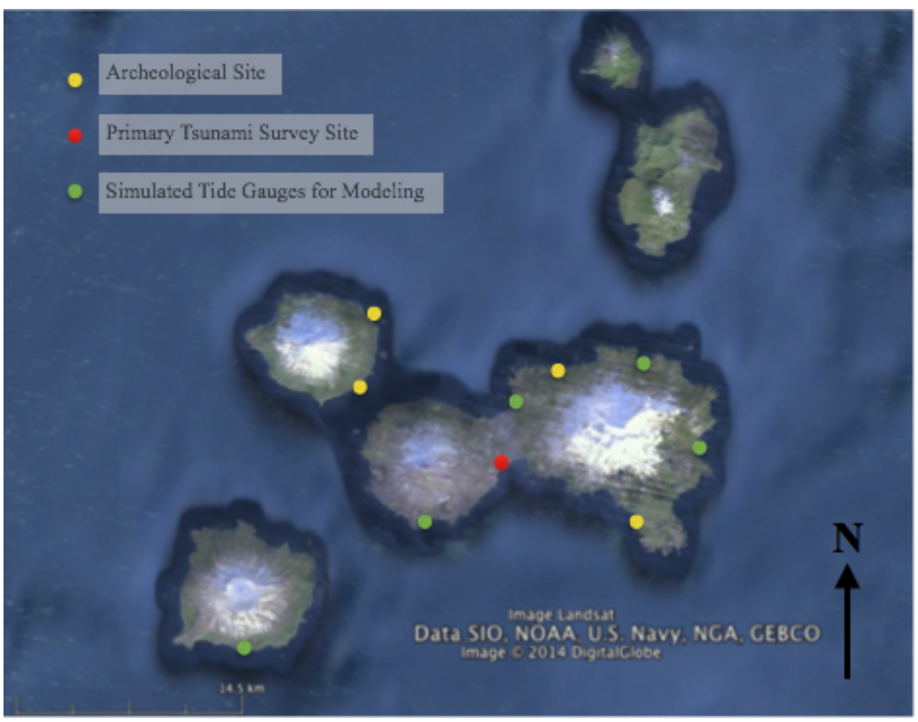

Figure 4:
Satellite image of the Islands of the Four Mountains with indicators of archeological sites for tsunami field surveys and important sites for modeling. Both locations will determine the runup and inundation of historical and paleotsunamis in order to see the impact on settlements. (Figure modified from Breanyn MacInnes, personal communications 2013).