PROPOSAL:
Evidence for Ancient Earthquakeson the Pacific Rim from the Alaska-Aleutian Subduction Zone.
Adrian M. Bender, 21 February 2012

Abstract

The Alaska-Aleutian subduction zone is a 3000 km-long active thrust fault at the northern edge of the Pacific Ocean, where the Pacific plate subducts beneath the North American plate. Rupture lengths and recurrence intervals of great (magnitude >8) earthquakes along the subduction zone are characterized by spatial and temporal heterogeneity. The contrasting nature of the Shumagin segment and the rupture zone of the 1964 great Alaskan earthquake exemplify this heterogeneity. Observed earthquake-related deformation, and the paleoseismic record at the 1964 rupture segment and elsewhere on the subduction zoneshows inboard subsidence and outboard uplift. Outboard coseismic uplift caused far-reaching destructive tsunamis in 1938 and 1964. While this area has been well studied, the record of earthquake deformation extends only to 4,000 years BP, and leading workers assert that more study is important for predictive modeling of future ruptures (e.g. Shennan et al., 2008). The Shumagin segment is historically observed to be aseismic, however the longevity of this aseismic interval is not known, and the preceding paleoseismic record of this segment is poorly understood. Evaluation of the paleoseismic record at the Shumagin seismic gap is necessary to determine the occurrence of past tsunamigenic earthquakes on this segment, and evaluate the probability of such earthquakes in the future. Here I propose a geological and geochemical investigation of the subduction zone paleoseismic record at the Shumagin gapand the 1964 earthquake rupture segment at study sites on Simeonof Island. Insight that this study will provide into the long term past of thesetectonically unique segments of the Alaska-Aleutian subduction zonehas the potential to be transformative by influencing the methods used to mitigate tsunami hazards throughout the Pacific Ocean basin “ring of fire”.

Specific Aims

The broad goal of this research is to improve understanding of the spatial and temporal heterogeneity of great earthquakes along the Alaska-Aleutian subduction zone, and to place the present day into the millennium-scale historical context of this boundary’s great earthquake cycles. Toward this broad goal, my proposed work aims to examine the paleoseismic record at the Shumagin and 1964 rupture segments of the subduction zone. I seek to determine whether or not earthquake-related deformation processes have driven relative sea level change at Simeonof Island, and whether or not a long-term history of earthquake-related subsidence exists at a field site in Knik Arm.

Introduction

As global population increases, so does coastal population density (McGranahan et al., 2007). This means that more life and property now exist along the Pacific Rim, at the edge of the greatest continuous seismogenic structure on the planet; the boundary between the subducting Pacific Plate and adjacently coupled continents known as the “ring of fire”.

Situated at the northern edge of the Pacific Ocean, the Alaska-Aleutian subduction zoneis one of Earth's most seismically active plate boundary segments, and contains the rupture zone of the Great Alaskan Earthquake of 1964 (M=9.2). Seafloor deformation during the 1964 and 1946 earthquakes generated tsunamis that caused death and destruction as far away as California and Hawaii, respectively (Carver and Plafker, 2008). The work I propose seeks to evaluate whether or not future earthquake-related tsunamis are probable on a currently aseismic segment of the subduction zone. The seismic gap hypothesis has emerged from the study of similar gaps on boundaries including the San Andreas Fault, California, and the Kuril Trench, Russia, which have been observed to give rise to great earthquakes. The seismic gap hypothesis generally states that segments of a fault that have not ruptured or undergone displacement over long time intervals on a similar magnitude to adjacent segments are likely sources of future earthquakes (McCann et al., 1979).

Seismicity along the subduction zone is characterized by spatial and temporal heterogeneity(Carver and Plafker, 2008;Freymueller et al., 2008;Shennan et al., 2008). An example of this spatial heterogeneity is this structure's along-strike variance between locked seismogenic segments, and gaps in seismicity (see figure 1). The 1964 earthquake rupture zone is well studied and exemplifies a locked seismogenic segment, while the Shumagin segment isaso-called seismic gap.

The historically aseismic behaviorof the Shumagin segment, or Shumagin Gap,has led previous workers to identify it as a likely point of long-term strain accumulation along the subduction zone, and a potential segment of impending large magnitude earthquake rupture (Davies et al., 1981;McCann et al., 1979). Geodetic data collected over the past 20 years, depicted in figure 2, shows that plate coupling at the Shumagin Gap is characterized not by strain accumulation, but by aseismic slip (Freymueller et al., 2008).

The historical longevity of this aseismic slip is not known, but limited geologic evidence suggests that the Shumagin Gap may have undergone episodes of earthquake related crustal deformation in the past 6000 years (Carver and Plafker, 2008;Winslow and Johnson, 1989;Witter, personal comm.).Understanding the paleoseismic record of the Shumagin Gap is essential for givingcontext to the current aseismic interval inthe earthquake cycle (e.g. figure 2) that may be characteristic of this segment, and to forecast future earthquakeand tsunami hazards that may emerge fromit. Preliminary investigation of sediment cores recently collected on Simeonof Island in the

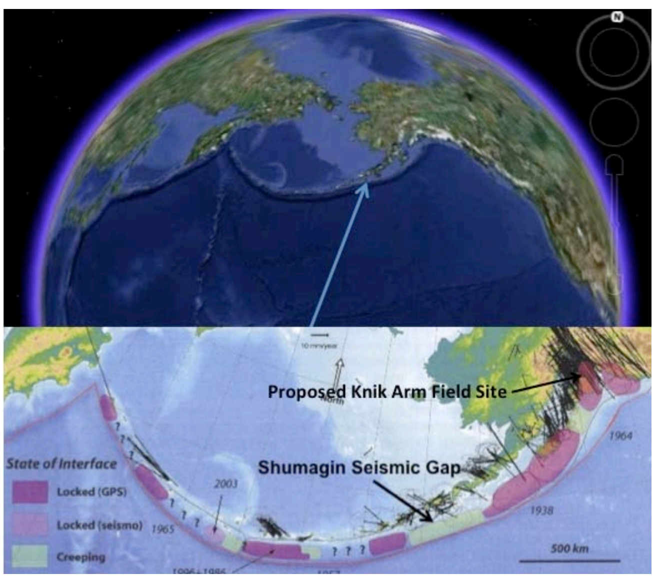

Figure 1: Google earth image of the Alaska-Aleutian subduction zone. Inset depicts study locations and spatial variance in the modern state of the interface between the subducting Pacific Plate and the North American Plate along the subduction zone, as inferred from geodetic and seismologic methods. Dates adjacent to locked zones are for large earthquakes (1938-2003) on those segments. Inset modified from (Freymueller et al., 2008).

outer Shumagin segment provide compelling information toward this end, but analytical work remains to be done.Workers in this field [e.g. (Cohen and Freymueller, 2004;Shennan et al., 2008) state that paleoseismic, seismologic, geologic, and geodetic data are all essential for understanding earthquake-related crustal deformation. The 1964 earthquake rupture segment (figure 1, inset, and figure 3) is well studied from these essential vantages.

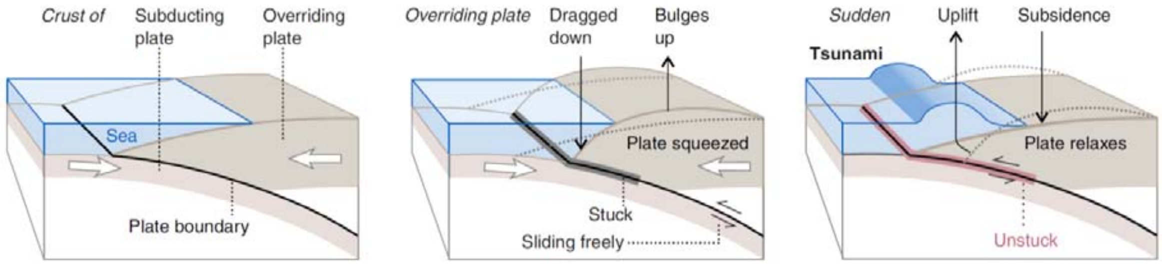

Figure 2: A depiction of the earthquake deformation cycle and resulting tsunami wave. Taken from (Atwater et. al., 2005).

The 1964 rupture segment of the subduction zone is east of the Shumagin Gap, and exhibits earthquake-related crustal deformation that was documented by Plafker (1965)and is depicted in figure 2. Coseismic deformation on the 1964 rupture segment (figure 3) is characterized by uplift outboard of a zone of zero-change, and subsidence inboard, followed by a long-term period of crustal readjustment (Plafker, 1965; Carver and Plafker, 2008).Seafloor deformation above the subduction zoneof the style observed during the 1964 earthquake hashistorically generated Pacific Ocean-wide tsunamis with impacts of varying severity, inferring a general similarity in earthquake deformation style along the subduction zone(Carver and Plafker, 2008;Davies et al., 1981;Witter, personal communication).

Shennan et al. (2008) assert that while the 1964 rupture zone is the best-studied segment of the subduction zone, much work remains to be done in understanding its long-term seismic behavior. Ghost forests are stands of dead trees, submerged during earthquake-driven subsidence and consequently drowned by saline water, and are ubiquitous in subsided tidal flats in coastal south-central Alaska inboard of the 1964 earthquake rupture. An unexamined ghost forest in Knik Arm likely contains insightful paleoseismic data, and is a good example of work on this segment that remains to be done.Because coseismic deformation observed historically and in the paleoseismic record on the 1964 rupture is characterized by inboard subsidence, I expect to findlong-term evidence for coseismic subsidence at the Knik Arm ghost forest.

Sedimentary evidence above the 1964 rupture records great earthquakes that cause land subsidence inboard and uplift seaward. If the earthquake cycle in the Shumagin segmentis similar to that of the 1964rupture, then I expect to find evidence of past earthquake-related uplift on Simeonof Island.Seeking evidence for paleoseismic deformation in the Shumagin seismic gap is a test of the global seismic gap hypothesis. Evidence for past uplift on Simeonof Island would provide support for the hypothesis, and indicate that future earthquakes are likely on the Shumagin gap. Lack of evidence for past uplift on Simeonof Island would refute the applicability of the seismic gap hypothesis to the Shumagin segment, and suggest some other cause, possibly postglacial adjustment, for relative sea level change.

Project Design

Dr. LeeAnn Munk (UAA) and Dr. Robert Witter (USGS) will advise the project I propose. Dr. Witter and colleagues cored tidal lagoon sediment seaward of the lowest of a set of possible marine terraces in 2011on Simeonof Island, an outer island in the Shumagin Seismic Gap, to examine the paleoseismic record they may contain. They have granted me access to study the geochemistry of these sediments. I propose furthercoring at a new field site in Knik Arm, inboard of the 1964 earthquake rupture segment, to further develop the record of earthquake related deformation on this segment.

Sediment cores from coastal marsh environments are powerful tools in paleoseismic interpretation because their stratigraphy records relative sea level changes, often between terrestrial peats, saline marshes, tidal muds and sands,caused by coseismic crustal deformation. Diatoms, organic ^{14}C, tephra, and environmentally sensitive biota provide dates and support stratigraphic interpretation of depositional environments(Shennan et al., 2008;Carver and Plafker, 2008;Atwater et al., 2005). Preliminary investigation of Simeonof Island cores suggest that the Island has not experienced a “recent” episode of uplift relative to sea level, but instead has been slowly submerging over the past few thousand years (Witter, personal communication). I propose to conduct detailed geologic and geochemical lab analyses on these cores to interpret the sea level record they may contain, thereby testing this idea.

I will conduct my geological analysis and geochemical sampling at the Alaska Volcano Observatory (AVO) lab facilities. Geologic analyses will seek toidentify stratigraphic relationships between sedimentary units deposited in marine environments (e.g. marine sand, mud) and terrestrial/tidal environments (e.g. terrestrial/tidal peats). The relative position of these sea level-sensitive units will indicate how the land surface-sea level interface has fluctuated over time. Dr. Witter has conducted his own geologic analyses of Simeonof Island cores; comparison of our observations will strengthen the overall geologic interpretation of the paleoseismic stratigraphy the cores contain.

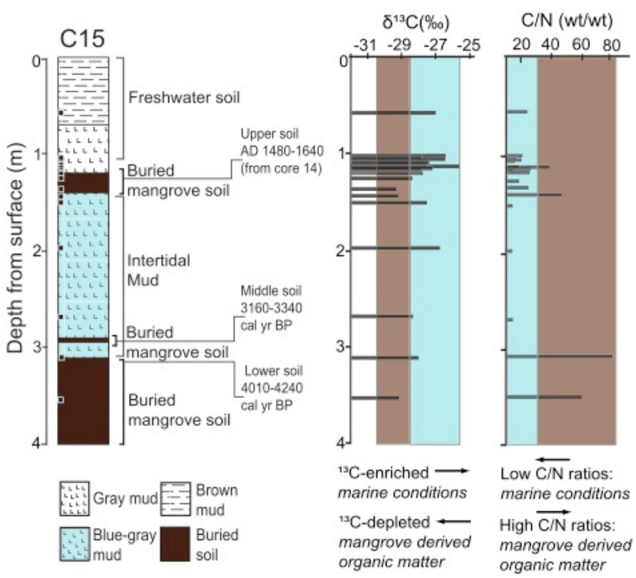

Figure 3: Geological and geochemical ($\delta^{13}C$ and C:N)data from a sediment core in coseismic subsidence stratigraphy inboard of the Sunda Subduction zone, Padang, Sumatra. Modified from (Dura et al., 2011).

With Dr. Witter’s oversight I willsample organic units for C-14 dating to quantify the timing of relative sea level change in one Simeonof core and the Knik Arm cores. To further quantify our interpretations, I propose to sample these coresfor analyses of$\delta^{13}C$,$\delta^{15}N$, C:N ratio, and trace element content. The use of $\delta^{13}C$ and C:N ratios as sea level indicators is an emergent field of study. Even more innovative is the recent application of these geochemical tools to paleoseismology. Kemp et al. (2010) successfully used $\delta^{13}C$ content of sea level sensitive plant species to reconstruct Holocene sea level in North Carolina, USA, generally finding $\delta^{13}C$ enrichment in marine and tidal plant matter, and $\delta^{15}N$ enrichment in decomposed terrestrial plant matter. Dura et al. (2011) analyzed the$\delta^{13}C$ and C:N content of a sediment core inboard of the Sunda Subduction zone, Sumatra, to corroborate their geologic observations, generally finding low $\delta^{13}C$ and enriched C:N values in brackish terrestrial deposits, and enriched$\delta^{13}C$ corresponding with low C:N values in marine-derived deposits (figure 3). The Sunda Subduction zone is tectonically similar to the Alaska-Aleutian Subduction zone, and is the rupture source for the devastating M 9.1 2004 Indonesian Earthquake and resultant tsunami that killed 227,898 people and caused $10 billion damage.

Ouruse of stable isotopes will be similar to that of Dura et al. (2011). Coseismic crustal deformation submerges tidal marsh sediments in the euphotic zone of the ocean, or uplifts euphotic zone sediments to supratidal elevations. The euphotic zone of Arctic seawater has a characteristic average $\delta^{13}C$ value of -23.4%$_0$ (Hoefs, 2009). Pore water at the sediment-water interface closely matches the adjacent marine average $\delta^{13}C$ values, with steep gradients in the first few centimeters of sediment depth, and additional $\delta^{13}C$ enrichment of organic sediment can be caused by bacterial methanogenesis (Hoefs, 2009).Episodic perturbation of the sediment-water interface elevation due to coseismic crustal deformation likely produces a fluctuation of sedimentary $\delta^{13}C$ values that peak near -23.4%$_0$ at times of eustatic equilibrium with variance in values by material type (e.g. higher values in peats, steeper gradients in tidal muds). $\delta^{15}N$ of particulate organic matter from the oceans should have an enriched signature relative to that from terrestrial sources (Hoefs, 2009), therefore this signature can also lead to understanding of the onset of seawater inundation. A study conducted on eastern Beringian grasses found mean $\delta^{13}C$ values for wet habitats of -29.1‰ (Wooller et al., 2007). Because the peats we observe in stratigraphy are generally derived from dune grass of similar environment to the eastern Beringian study, I will compare the terrestrial $\delta^{13}C$ values I obtain to the value for wet habitat Beringian grasses for my interpretation.

Additionally, seawater can be enriched in certain trace elements relative to terrestrial water (Faure, 1998), therefore I expect a positive shift in trace element concentrations reflected in the sediment cores as a result of sea level rise. Furthermore, I expect that overall C:N ratio values will be greater in terrestrial peats, and lesserin marine deposits, as discovered in Sumatra by Dura, et al. (2011). If characteristic submergence-emergencevalues of average $\delta^{13}C$, $\delta^{15}N$, C:N and trace elements are observable in cores, theyshould support our geologic interpretations of paleoseismic stratigraphy in cores. Samples will be 1 cubic centimeter in volume, and will be taken in intervals determined by the size and distribution of sedimentary units. I will prepare these samples for analysis in the ASET lab on the UAA campus following methods established in Dr. Munks geochemistry lab.

The final component of my proposed work is to evaluate whether or not the possible marine terraces on Simeonof Island provide geomorphologic evidence for episodes of past uplift. I will do this by mapping and constructing topographic profiles of these landforms using remote imagery and topographic maps. This will facilitate a semi-quantitative assessment of landform morphological characteristics in comparison to known marine terraces. Collectively,the project components that I outline here should serve to support or refute my hypotheses that the Knik arm field site preserves a long-term record of coseismic subsidence, and that the Shumagin segment is presently in an aseismic interval of an earthquake cycle spatially similar to but temporally distinct from those of other subduction zone segments.

Anticipated Results

Below is an outline of the results that I anticipate from this proposed work.

(1) **Geologic Analysis:**

a. My geologic analysis of Simeonof Island and Knik Arm cores will provide a basic understanding of the stratigraphic record of depositional environments.

b. The stratigraphic sequences should contain marine sands sharply contacting terrestrial soils or peats. If the Shumagin seismic gap has undergone past cycles of earthquake deformation, then episodes of coseismic uplift (marine deposits overlain by terrestrial) should be recorded in the stratigraphy of cores taken at Shumagin Island. Similarly, I expect that the stratigraphy of cores to be taken at Knik Arm will preserve a history of coseismic subsidence (terrestrial deposits sharply overlain by marine).

(2) **Geochemical Analysis:**

a. The stratigraphic units I interpret as marine deposits will be enriched in $\delta^{13}C$, $\delta^{15}N$ and trace elements, while terrestrial deposits will be C:N enriched. If an observable submergence-emergence C and N spectrum emerges from these cores, I expect it to be approximately opposite between sites because the earthquake related deformation cycles are mechanically opposite.

(3) Geomorphologic Analysis:

a. The geomorphic maps and profiles should reveal topography and landforms that support my hypotheses. Past episodic uplift at Simeonof Island will be supported bythe presence of marine terraces and/or raised shorelines, andstepped topography decreasing in elevation toward sea level Past episodic subsidence at Knik Arm will be supported by topographic depression and lineaments between subsided and relatively unaffected geologic units.

Project Budget

Category:	***Fran Ulmer Transformative Award funds:***
Services	
N and C isotopic analysis of Simeonof Island and Knik Arm cores ($7.50/sample x 40 samples)	$300
Trace element analysis of Simeonof Island and Knik Arm Cores ($45/sample x 40 samples)	$1,800
Radiocarbon dating of Knik Arm cores ($595/sample x 4 samples)	$2,380
Undergraduate Symposium Poster printing costs	$44
TOTAL SERVICES	**$4,524**
Travel	
Knik Arm field days (4 days x 80 miles/day X $0.55/mile)	$176
Supplies	
Adobe Illustrator Software	$200
Miscellaneous unforeseen supplies	$100
TOTAL SUPPLIES	**$300**
TOTAL BUDGET REQUEST	**$5,000**

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Project Timeline: Spring 2012-Spring 2013

Work:	***Completed by:***
Background Research	1 April 2012
In-lab analysis of Simeonof Island study areas: Geology, geochemistry, geomorphology.	15 May 2012
Knik Arm sediment coring; field site reconnaissance, coring of marsh sediment, field notes.	10 August 2012
In-lab analysis of Knik Arm study area: Geology, geochemistry, geomorphology.	15 September 2012
Data analysis, synthesis, figures, and writing complete for review	1 November 2012
Present at AGU Fall Meeting	6 December 2012
Undergraduate Research Symposium Presentation	Mid-April 2013
Expenditures submitted	15 May 2012
Final report submitted	30 May 2012