**Modeling of the 2010 Tsunami in South-Central Chile**

Thesis Proposal
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**Problem To Be Addressed**

A long-term goal of paleotsunami studies is to predict paleoequake parameters based on tsunami deposits found on land. The coast of Chile provides an excellent study area to try to accomplish this goal, as the country has a long history of historical (written records) earthquakes (Figure 1), and paleoearthquakes (geologic records of tsunami deposits). Written records are available for the 1575, 1737, 1837, and 1960 earthquakes and can include descriptions of earthquake shaking, tsunamis, and coastal uplift (Figure 1). Most data prior to the 1960 earthquake is limited to eyewitness written accounts from Chileans and Spanish conquistadors, or estimations from modern studies (i.e. fault rupture locations) (Figure 2). The 2010 earthquake and tsunami are the most recent and best-documented in the area. Datasets of inundation, run-up heights, and deposit descriptions from post-tsunami surveys and fault slip parameters from co-seismic slip models provide an opportunity to conduct a detailed study of the 2010 deposits. This will give a better understanding of the source characteristics and magnitude of the 2010 subduction zone rupture that generated the tsunami. Ultimately, the 2010 event can be used as a case study to apply to paleoeearthquakes where tsunami deposits are the only records available.
Figure 1: Inset maps (a and b) to show location of b, south-central Chile. A summary of written evidence, by location, from the effects of the 1960 earthquake and historical earthquakes. This includes evidence of: tsunamis, earthquake shaking, and coastal uplift and subsidence. This information is compiled from eyewitness accounts from Spanish Conquistadores and Chileans (Figure from Cisternas et al., 2005).
Background

The central and south-central coast of Chile lies above a continental margin, where the Nazca plate subducts slightly obliquely beneath the South American plate at a rate of 66 mm/yr (Moreno et al., 2012) (Figures 3 and 4). Significant strain accumulation along the offshore subduction zone results in megathrust earthquakes, which are great (Mw>8) earthquakes on the subduction zone, with a recurrence interval of about one per 100-200 years in any given segment of the margin (Moreno et al., 2010). Additionally, this convergent margin has the potential to generate devastating tsunamis.

The February 27, 2010 Mw 8.8 earthquake and tsunami that struck the Maule and Bio-Bio regions (Figure 4) was destructive to human life and property. It also substantially altered the coastal landscape, leaving a depositional record that may be preserved at many locations along the central coast of Chile (Morton et al., 2010). The
earthquake ruptured ~500km of the subduction zone and also ruptured the Concepción-Constitución seismic gap, where the last great earthquakes occurred in 1835 (Mw~8.5) in the south-central portion and 1928 (Mw~8.0) on the north-central portion of the rupture area (Moreno et al., 2012).

Tsunami runup, measured by post-tsunami surveys, peaked at Constitución at 26.2 m and 29 m, decreasing to the north with runup heights typically between 5m-10m and uniformly below 5m in the northernmost Valparaíso area (Annunziato et al., 2011; Fritz et al., 2011). To the south between Constitución and Punta Morguilla, runup heights were variable between 5m-15m. Further south of Punta Morguilla, heights were mostly below 5m with the exception of Tirúa and Isla Mocha, where runup was 20 m and 23 m respectively (Fritz et al. 2010). Eyewitnesses of the tsunami reported one to four main waves, with the first wave arriving within 30 minutes of the earthquake (Annunziato et al., 2011; Fritz et al., 2011; Morton et al., 2010). Tide gauge data (reported as half of the maximum wave height, minus normal tide) recorded data all over the Pacific, including: 1.79 m at Hive Oa Island, Marquesas Islands, French Polynesia; 1.00 m in Gisborne, New Zealand; and 1.14 m in Severo-Kurilsk, Paramushir Island, Russia. Eyewitness water height was also 1.20 m in Pismo Beach, California (NGDC/WDS).

Figure 3: Box in green contains all of my study areas within south-central Chile in relation to South America. The Peru-Chile trench is traced in yellow.
Figure 4: Tectonic setting within the study area, south-central Chile. The Nazca plate subducts beneath the South American plate at 66 mm/yr in this general location (Moreno et al., 2012). Study areas are marked in yellow and Santiago is marked in green for reference. The 2010 rupture area from is marked within the pink boundary and red star marks the epicenter location, both from Moreno et al. (2012).
Objectives

The first objective of this study is to model the 2010 earthquake using published earthquake models to simulate tsunami runup and inundation with the GeoClaw tsunami modeling code. The simulated tsunami runup and inundation values will be compared to 1) published runup and inundation values based on post-tsunami survey observations, and 2) runup and inundation maps based on our own and previously published field surveys of deposits from the 2010 tsunami.

From these comparisons, I will modify earthquake parameters to produce two “best fit” tsunami simulations to these two types of field observations. The comparison with post-tsunami survey observations will elucidate characteristics of the earthquake most important for tsunami generation. The comparison with tsunami deposits will reveal the minimum earthquake magnitude needed to produce the observed tsunami deposits, an important analysis for using tsunami deposits to interpret paleoearthquakes.

In order to ultimately use paleotsunamis to estimate paleoearthquake slip distributions, it is also important to consider that the sedimentary characteristics of deposits may change during burial and preservation. The second objective of this study is to compare the deposits immediately after the tsunami in 2010 with observations from revisiting the same sites 5 years later. Deposit characteristics we will measure to determine taphonomic processes include: thickness, grain size, normal grading, sedimentary structures, incipient soil development and accumulation of organic material.

Hypotheses

I hypothesize that the slip distribution I create in GeoClaw to create a “best fit” scenario between simulated tsunami runup and inundation and field survey runup and inundation will differ slightly from the published slip models. The input data used to simulate the tsunami and create the slip distribution will create a good simulation of the tsunami and its effects, but will not be perfect. Most published co-seismic slip models use geodetic data and broadband signals, which are useful, but models may not fully represent aspects of seafloor displacement that is relevant to creating the tsunami (c.f. Lorito et al., 2011). Therefore, I predict the published slip models that include tsunami data will be the most similar to the slip distributions I will create in GeoClaw. I will be comparing at least 75 published field survey runup and inundation values to simulated runup and inundation values in locations that span throughout the general rupture area, which I anticipate will provide good spatial coverage. However, I anticipate that other factors such as bathymetry, shoreline orientation, and topography will be represented well, but not perfectly, in the model, causing simulated runup and inundation to be slightly different than the published field surveys. While it may be necessary to adjust the earthquake magnitude and slip parameters (latitude, longitude, depth, slip, rake, strike, dip) to create a best fit, the slip distribution created in GeoClaw will be located in the same general area and will display similar locations of maximum slip along the subduction zone as the published slip models. This will
confirm that GeoClaw can be used when modeling to runup and inundation field measurements for the 2010 Chile event.

Additionally, I hypothesize that the slip distribution I create in GeoClaw to create the second “best fit” scenario between simulated inundation and runup and the deposits on land will differ from the published fault slip distributions and will underestimate the earthquake magnitude to less than 8.8. This “best fit” tsunami simulation and slip distribution will be greatly dependent on the sediment deposit data. The deposit dataset is smaller in number than the post-tsunami survey runup and inundation measurements and may not cover the entire slip area. Fewer data points can result in a truncated slip distribution. Also, the tsunami deposits alone will only indicate minimum runup values due to the deposition characteristics and the possibility of deposit erosion since initial deposition. I anticipate it will be necessary to adjust the earthquake magnitude and slip parameters to create the “best fit”. I anticipate that modeling with only tsunami deposit data in GeoClaw will be possible, but with limitations.

When comparing the tsunami deposits from 2010 to 2015, I hypothesize the tsunami deposit inland extent and thickness will be reduced by no more than half in comparison to what was measured in 2010. Deposit inland extent and thickness can decrease from wind erosion and from human activity. Bioturbation will be present at some locations and may erase signs of normal grading and sedimentary structures. By 2015, I anticipate deposits will be covered by sand (different from the tsunami deposit), incipient soil, or organic material.

**Prior Work**

Many research groups conducted surveys of tsunami evidence within a relatively short time after the tsunami on February 27, 2010, including: Annunziato et al. (2011), Fritz et al. (2011), and Morton et al. (2011). These groups selected sites to the north and south of the epicenter where they predicted sites would have good preservation (Morton et al., 2011). From March 27-30, 2010, Annunziato et al. (2011) took runup and inundation measurements, conducted eyewitness interviews, noted evidence of uplift, and took a number of photos of the damage at a number of locations that spanned 250 km of the coast between Licanten to Arauco (34.9-36.5 deg.S.Lat.). Fritz et al. (2011) measured tsunami runup, inundation, flow depth, and wave induced deposition or erosion, assessed structural damage, and conducted eyewitness interviews. Their survey took place from March 7-24th and May 21-22, 2010 over 800 km of the coast from Quintero to Mehuín (32.7-39.4 deg.S.Lat), as well as Santa María Island (37.0 deg S Lat), Juan Fernández Archipelago (33.6 deg.S.Lat.), Rapa Nui (27.0 deg.S.Lat.), and Mocha Island (38.3 deg.S.Lat.). Morton et al. (2011) measured flow depths, flow directions, vertical erosion, deposit thickness, and maximum clast sizes at each study site, topographic profiles and inundation at four sites, and flow direction histories at two sites. Their survey took place from April 24-May 2, 2010 along a 200 km section of the coast from La Trinchera to Talcahuano (35.1-36.7 deg.S.Lat.). All three teams agreed the tsunami runup elevations and morphological impacts were highly variable as a result of variations in tsunami wave heights,
Many research groups have published co-seismic fault slip models of the 2010 event. Each group used a unique combination of data including GPS, teleseismic waves, InSAR, tsunami waveforms, and land level changes to create their own co-seismic slip models. The primary differences among the 17 co-seismic slip models are the locations and depth of the maximum slip. For example, by inverting teleseismic P and SH waves, Lay et al. (2010)’s solution resulted in a finite-fault slip distribution with a maximum slip of 20 m concentrated in a shallow northern patch (Figure 5). Delouis et al. (2010) inverted teleseismic records, InSAR and High Rate GPS data and produced a slip model with two concentrations of maximum slip of 21 m to the north and 13 m to the south of the hypocenter all within 50 km depth (Figure 6). Lorito et al. (2011) used tsunami, InSAR, GPS, and land level changes to produce a slip model with a major 18-19 m slip patch to the north of the epicenter at depth between 25-40 km and a minor 9-10 m slip patch further to the south at a similar depth of the major patch (Figure 7). These variations can produce earthquakes with different seafloor deformation patterns and therefore a different tsunami model of coastal inundation and run up.

![Figure 5: Fault slip model by Lay et al. (2010). The 2010 epicenter is shown with a grey star and slip vectors are shown as grey arrows. Historical rupture locations are shown as either pink areas or heavy dashed lines.](image)
Figure 6: Fault slip model by Delouis et al. (2010). 2010 Epicenter marked with a white star. Red and blue arrows are observed and computed horizontal displacement from GPS and red/yellow rings are observed (outer ring) and computed (inner area) GPS vertical displacement. The insert is unwrapped InSAR data. The 1985 and 1960 rupture areas are included.
Figure 7: Co-seismic fault slip model by Lorito et al. (2011). The 2010 epicenter is marked with a red star and slip direction (rake) is represented by white arrows. Subsidence on the coast is outlined with 20 cm interval dashed lines and 1 m interval thin solid lines for uplift. The 1985, 1928, and 1960 epicenters are marked with yellow stars and their rupture areas are outlined in a heavy black line. The 1835 Concepción-Constitución seismic gap is marked with a heavy black dashed line.

Methods
To test my hypothesis, GeoClaw, an open-source software for modeling two-dimensional shallow-water wave equations, will be used to simulate the 2010 tsunami. Using GeoClaw requires data to specify the bathymetry of the ocean and coastal regions, the topography onshore of the inundated regions, and the motion of the seafloor that initiates the tsunami. Using earthquake parameters from the published co-seismic fault slip models, GeoClaw will create a slip event along the subduction zone
with a defined earthquake magnitude, tsunami waves, and runup and inundation values of the wave on land.

These simulated tsunami runup and inundation values will be compared to 1) published runup and inundation values based on observations immediately following the tsunami, and 2) runup and inundation maps based on our own and previously published field surveys of deposits from the 2010 tsunami. Based on this comparison, I will adjust the earthquake magnitude and slip parameters (latitude, longitude, depth, slip, rake, strike, dip) to produce two tsunami “best fit” models to better match these two types of field observations. By comparing my two “best fit” slip distributions and the published slip models, this will provide more information about the source event location, depth, slip rate, slip angle, and fault orientation that created the 2010 tsunami hazards (runup and inundation). Also, this will reveal the minimum earthquake magnitude needed to produce the measured tsunami deposits and show how well the earthquake and tsunami can be modeled from deposits only. This can be applied to paleoearthquakes where tsunami deposits are the only reliable records available.

Fieldwork in Chile will be conducted for two weeks in January 2015 to compare the tsunami deposits with descriptions of the same deposits conducted a few weeks after the 2010 tsunami. While in the field, the coastal areas of Lipimavida, La Trinchera, Constitución, Coliumo, Quidico, Tirúa, and Tubul (Figure 4) will be visited because published results by Morton et al. (2011), Fritz et al. (2010), Annunziato et al. (2011) and unpublished data from Ely have found evidence of the 2010 event in these areas. At each study site pits will be dug at the exact locations (within GPS error) visited by Morton, Fritz, Annunziato, and Ely as well as other locations we choose within previously measured inundation limits. Each deposit thickness will be measured and any observations of normal grading, sedimentary structures, incipient soil development, and overlying organic material will be noted. Topographic transects will also be measured to investigate the landward extent of the 2010 deposits in 2015. In the lab, the sediments will be analyzed for grain size using the Mastersizer 2000, which will provide the deposit grain size and confirm field observations of normal grading. When possible, interviews of local residents that witnessed the tsunami first hand will be conducted to get more data about the tsunami’s inland extent and whether multiple waves inundated the area.

**Significance Of Research/Benefits**

The central and south-central coast of Chile contains the greatest population density in the country and has encountered great infrastructure and human loss from the 1960 and 2010 tsunamis. To help mitigate destruction from future events, it is necessary to gain a better understanding of past tsunamis and the subduction zone ruptures that generated them. Adjusting published co-seismic fault slip models in GeoClaw to create a “best-fit” scenario simulating wave runup and inundation close to field observations and sediment deposits can give a better understanding of the source and magnitude of the 2010 earthquake that generated the tsunami. Additionally, studying the change of deposits in the geologic record over time can provide key insights into how tsunami deposits are preserved, which is important when working with paleodeposit that may have been altered since initial deposition. My research can
be used as a case study that, if proves to be successful, can be applied to earlier paleoearthquake and tsunami events where seismic data is sparse or non-existent and the most reliable records are the tsunami deposits.

References


Delouis, et al. (2010), Slip Distribution of the February 27, 2010 Mw = 8.8 Maule Earthquake, Central Chile, from Static and High-Rate GPS, InSAR, and Broadband Teleseismic Data: SLIP DISTRIBUTION MAULE EARTHQUAKE, *Geophysical Research Letters*, 37.17.


National Geophysical Data Center / World Data Service (NGDC/WDS), Global Historical Tsunami Database. National Geophysical Data Center, NOAA, doi:10.7289/V5PN93H7 access date: 3/1/2015.


Schedule

*January 2015* - Field work in Chile

*April 2015* - Thesis proposal presentation
Spring 2015- Make bathymetry
Spring 2015 & Summer 2015- Setup model parameters & debug
Spring 2015 & Fall 2015- Sediment analysis
Fall 2015- Modeling to post-tsunami field surveys and sediment deposits
Fall 2015- Writing thesis
Feb 2016- First draft of thesis
May 2016- Thesis defense

Budget
Airfare for three: $4,000
Shuttle to/from Ellensburg and Seattle: $180
Food: $1,000
Lodging: $3,000
Rental car & gas: $950
Shipping samples: $150