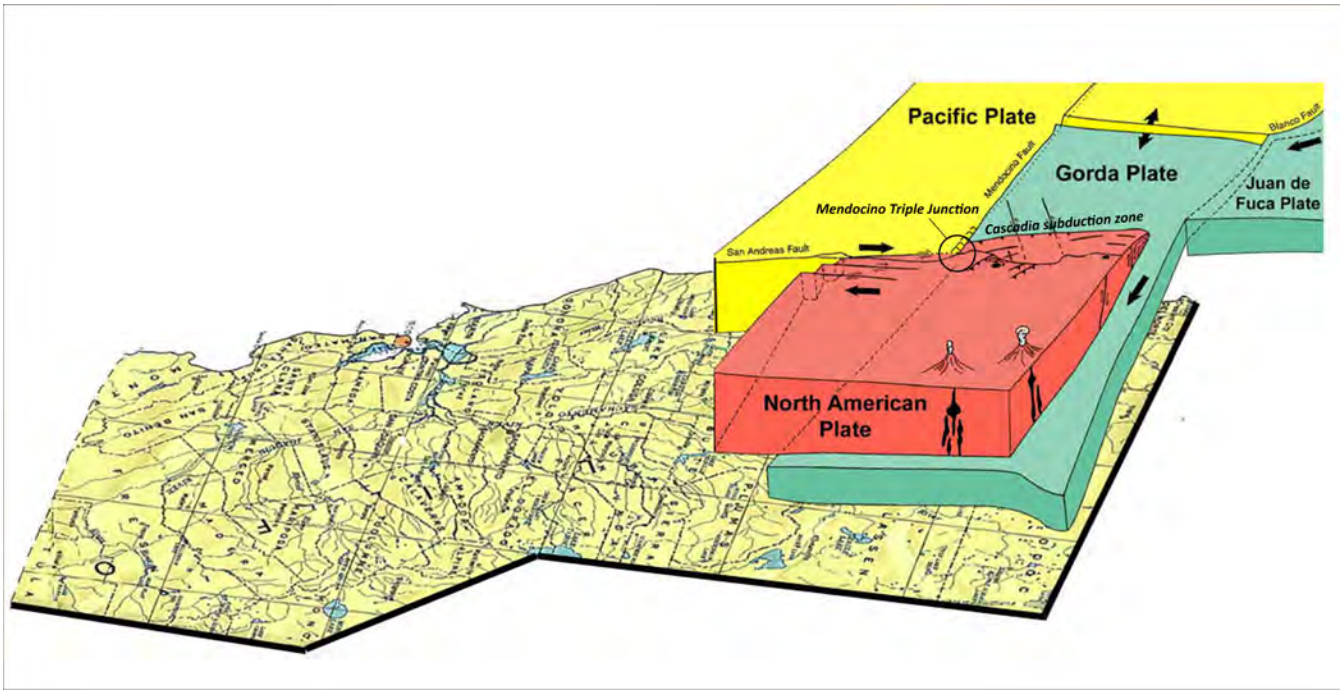
CEETEP Field Trip Guide
October 10, 2015

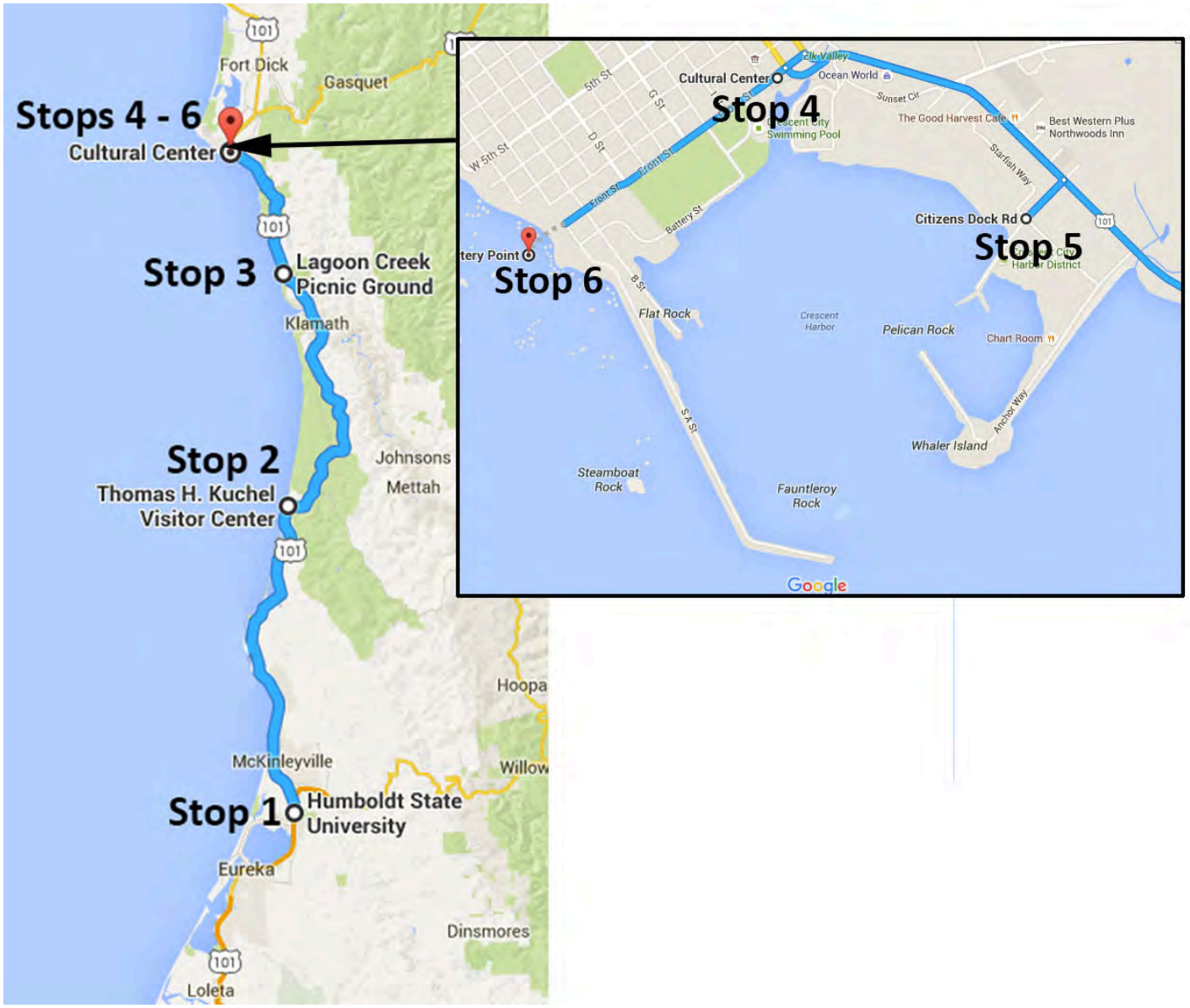




Cascadia EarthScope Earthquake and Tsunami Education Program (CEETEP)

October 9 - 12, 2015

Field Trip Stops



CEETEP Convener cell phone numbers
Bob Butler: 503-313-3908
Lori Dengler: 707-845-4960
Beth Pratt-Sitaula: 509-899-3480
Kerry Sherin: 707-845-4891

Field Trip Schedule

Stops	Location	arrive	leave	topics covered	guidebook page
	Van Matre Hall - Breakfast	7:30	8:00	Orientation to Humboldt Bay plate tectonic setting	4
1	HSU GPS station	8:00	8:45	Geometry of the southern Cascadia margin, monitoring earth movements, coseismic/interseismic deformation, complexities of the accretionary fold and thrust belt.	5
	Driving 8:45 - 9:30				
2	Redwood National Park Information Center (restrooms)	9:30	10:15	Native peoples of the area, oral history, reconstructing the last Cascadia earthquake & tsunami from oral history, correlating oral history with scientific data, using oral history to constrain tsunami maps, Orick TsunamiReady, multi hazard beach signs and folding tsunami preparedness into an all-hazards approach.	7
	Driving 10:15 - 10:45				
3	Lagoon Creek (restrooms)	10:45	11:15	Paleotsunami stratigraphy, not all Cascadia tsunamis (and earthquakes) are the same, tools of paleoseismology, Value of high and low coastal wetlands in recording paleo- tsunami history. Only large tsunamis captured at Lagoon Creek. Compare to Crescent City gouge core.	10
	Driving 11:15 - 11:45				
	Lunch - Crescent City Community Center	11:45	12:30		
4	Crescent City Tsunami Walk	12:30	1:30	What happened in 1964, the tsunami warning system and what would happen if the 1964 tsunami happened today, how a Cascadia tsunami would differ from 1964, evacuation and inundation maps - how they differ.	14
	Driving 1:30 - 1:45				
5	Crescent City Harbor	1:45	2:15	Marigrams and past tsunamis in Crescent City. What is so special about Crescent City and tsunami amplification, what happened in 2006 and 2011, harbor retrofit.	18
	Driving 2:15 - 2:30				
6	Battery Point Lighthouse	2:30	3:00	What happened in 1964, the complexities of the Cascadia fold and thrust belt (difference in sea mount density to the north and south), the big picture.	22
	Return to Arcata	3:00	4:30		

Introduction and Orientation

The Cascadia margin along the Northern California is unique because of the close proximity of the fold and thrust belt to the coast. In most of the world's subduction zones and the Cascadia margin offshore of Oregon and Washington, the highly deformed edge of the North American plate is far offshore. Onshore mapping and offshore marine reconnaissance studies reveal a complex series of Holocene folds and faults (Figure 1).

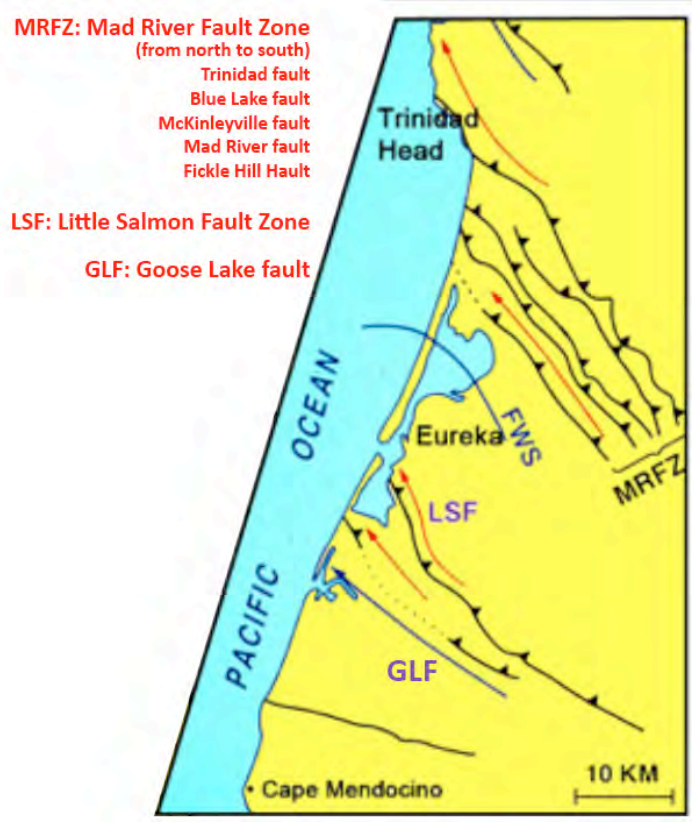


Figure 2: Mapped active faults in the Humboldt Bay region.

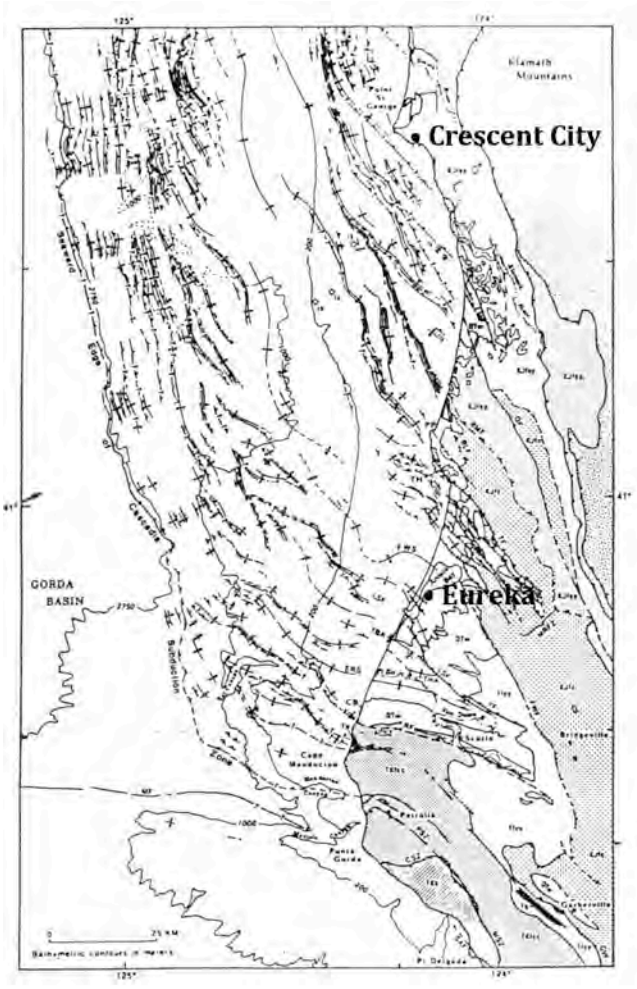


Figure 1: Mapped offshore and onshore faults part of the Cascadia fold and thrust belt..

The faults and folds are best studied in Humboldt County where seven thrust faults have been classified as active under California's Alquist-Priolo Special Studies fault zone identification legislation (Figure 2). The closest mapped fault to the HSU campus is the Fickle Hill fault, one strand of which cuts through campus and surfaces about 320 meters (1050 ft)) WSW of Van Matre Hall.

None of these faults have produced slip in the last 165 years of written history, although all show paleoseismic evidence of rupture within the last 10,000 years. Slip measurements suggest earthquakes as large as 7.8, if they occurred independently.

In addition to the close proximity of the Cascadia margin to the coast, Northern California tectonics are further complicated by the Mendocino triple junction (see front cover) 62 km (38 miles) SSW of Van Matre Hall, and faulting within the Gorda plate.

STOP 1: HSU GPS Station

The Humboldt State University Global Positioning Satellite (GPS) Station is located just east of the Lumberjack stadium, a short walk from Van Matre Hall (Figure 3). It is one of 11 stations operated by UNAVCO to monitor deformations at the southern end of the Cascadia subduction zone and the Mendocino triple junction.

Continuous GPS stations are able to track very small movements of a site relative to both horizontal and vertical axes.

Figure 3. HSU GPS site.

The instrument was installed in late 2005. The plot to the left (Figure 4) shows the record of movement since it was installed. Note the jump in the eastward movement on March 10, 2014 at the time of the magnitude 6.8 offshore earthquake.

The figures below show the network response during the 1994 and 2010 earthquakes. In both cases, land moved primarily to the east.

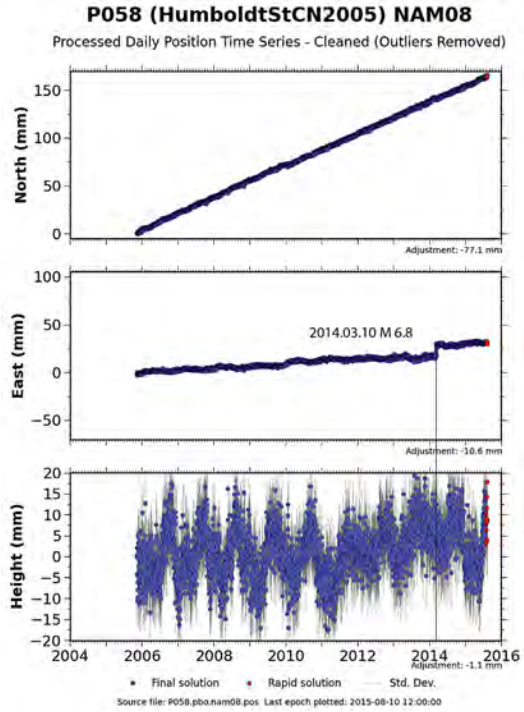


Figure 4. HSU GPS data.

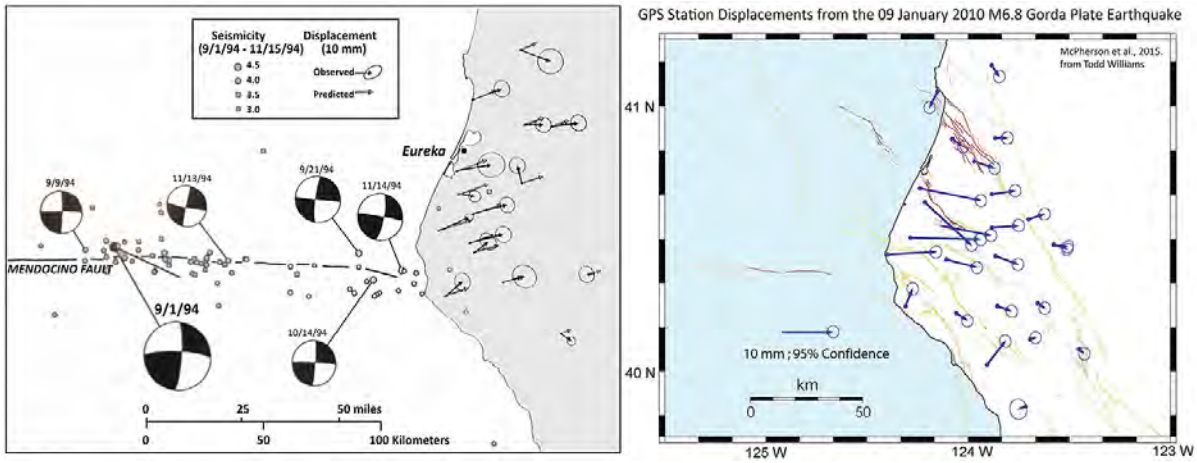
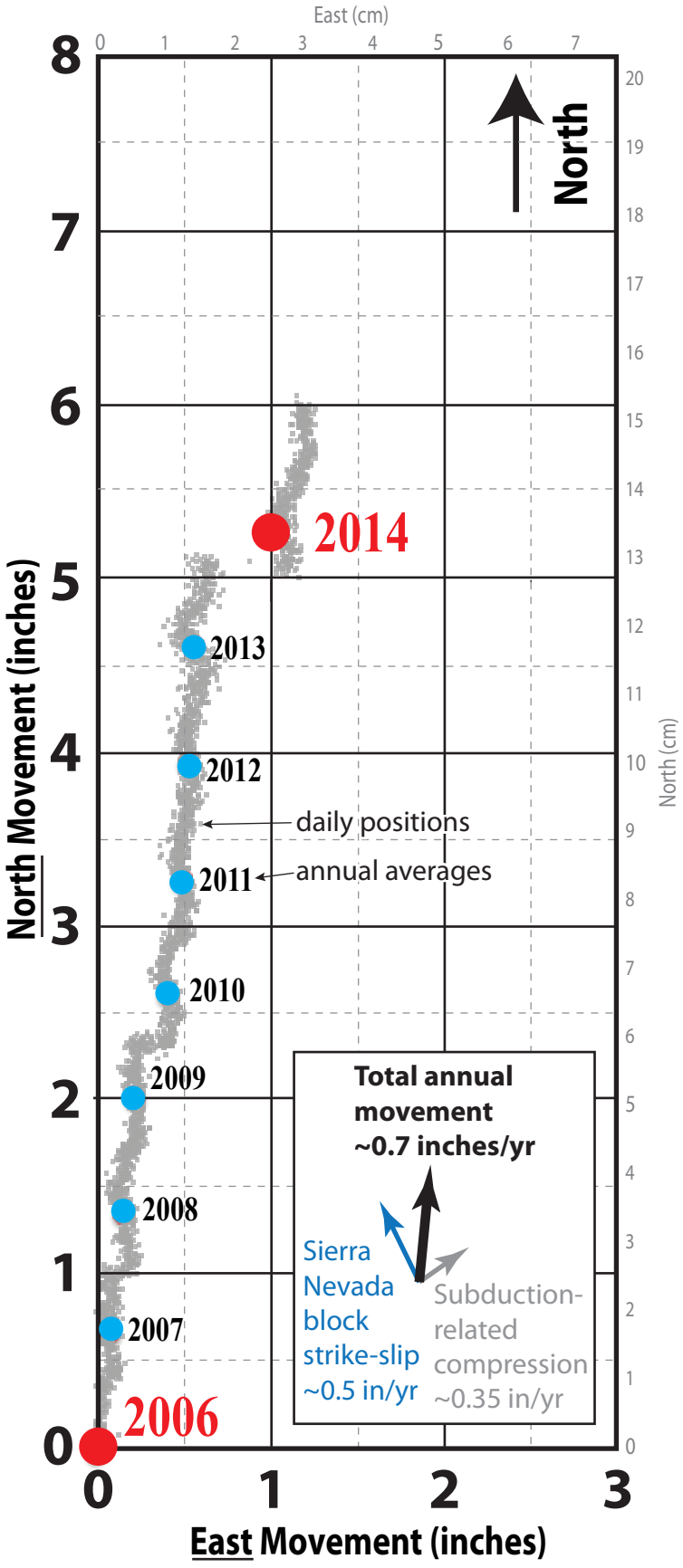


Figure 5. GPS array data comparing positions before and after the September 1, 1994 M 6.9 Mendocino fault earthquake and the March 10, 2010 M 6.8 offshore Gorda plate earthquake.

Arcata, California GPS Station

Yearly Movement, 2006 - 2014

(Referenced to North America's stable east)



Cut Here

The dots on this card show motion of the Arcata GPS station since 2006. Because the station is anchored into hard rock beneath the soil, the large dots represent the year-to-year movement of the Arcata region toward the north-northeast.

Orient this graph toward the north, tape it to the floor, and think about the questions below.

1. How far has the Arcata region moved since the year 2006? At what rate (inches per year) is the region moving in total? How much of this movement is due to Sierra Nevada block strike-slip motion?

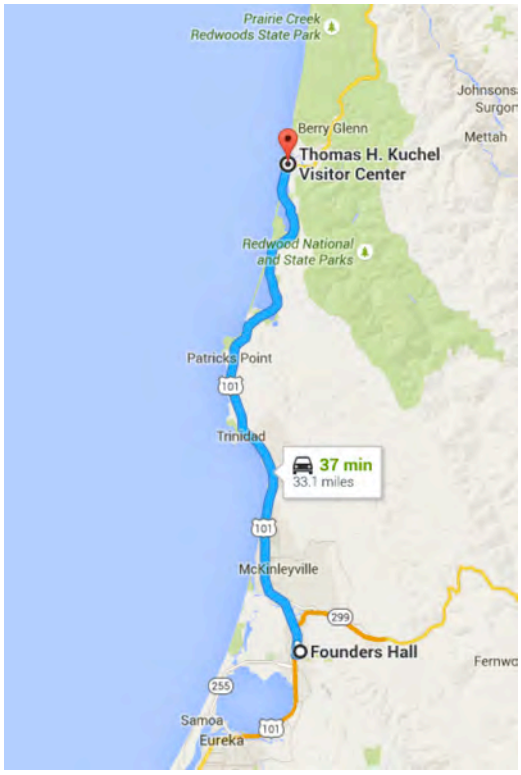
2. How much of this movement (inches per year) is due to subduction-related compression? The last Cascadia subduction-zone earthquake occurred in the year 1700. **What will happen to the Arcata region when the next big subduction earthquake occurs?**

3. Why do the daily timeseries have a sudden offset in early 2014? How much movement was measured? What direction was the movement?

Station P058 from the EarthScope Plate Boundary Observatory (**http://pbo.unavco.org**). GPS time series data provided by UNAVCO (**http://www.unavco.org**). Data as of August 14, 2015. Position offset -0.06 inches east and -0.5 inches north from the NAM08 P058 .cvs file to bring 2006 average to zero.

Card developed by the Cascadia EarthScope Earthquake and Tsunami Education Program (CEETEP; **http://ceetep.oregonstate.edu**) and UNAVCO. CEETEP is sponsored by a grant from the EarthScope Program (**http://www.earthscope.org**) of the National Science Foundation to Oregon State University, the University of Portland, and Central Washington University.

From the HSU campus, we drive north on U.S. Highway 101 to the Redwood National Park Information Center at the mouth of Redwood Creek.



STOP 2: Redwood National & State Parks Information Center

The Native peoples of the Pacific Northwest have a long oral history tradition. Some of the accounts provide vivid descriptions of earthquakes and tsunamis. Although many accounts were lost after European settlement, some were recorded by anthropologists at the turn of the century and others are still told today.

Figure 6. Tskerkr (center left) at the fishing village of Sigwetz near the present day location of the Information Center.

Three stories of the Yurok people who lived at or near this location are excerpted below.

How Prairie Became Ocean: "Where shall we make water to be? How will they live if we leave prairie there?" said Thunder. He said to Earthquake, "What do you think? I want water to be there, so that people may live." Then he (earthquake) started and arrived there, it will be easy for me to do that, to sink this prairie." so he ran about a little and the ground sank. So they (two) went south with one another. He kept sinking it: every little while there would be an earthquake, then another earthquake: that is what he was doing. And then the water would fill those (depressed) places. Then they went north together and did the same: they kept sinking the ground. The earth would quake and quake again and quake again. And the water was flowing all over.

And that is why it is thus, that everything is in the ocean that (lies) in front of us. The land sank where they had run about, (where) Earthquake had run about, Thunder had run about. One can see now that the water is deep-of course we do not know how deep it is-because it was a prairie.

Yurok legend told by Ann of Espeu, recorded by Kroeber

Earthquake and Thunder: Then Earthquake thought: "How will it be about the earth?" Thunder came and said, "It will be best if I help you when you shake." Earthquake said, "Well, I shall tear up the earth." Thunder said, "That's why I say we will be companions, because I shall go over the whole world and scare them" Earthquake said, "If I see the earth tilt, I can level it again" So he (Thunder) began to run, and leaped on trees and broke them down. Earthquake stayed still to listen to his running. Then he said to him, "Now you listen: I shall begin to run." He started. He shook the ground. He tore it and broke it to pieces. All the trees shook; some fell

Now that is the reason Earthquake goes to different places because in the beginning he did that, and did not encompass the world in one day. It is thus with him now: He cannot go entirely around in a day, so he goes part way, and as it were spends the night. In some places he shakes the earth hard, in some he shakes it a little. For he did that in the beginning and does it now."

Yurok legend told by Tskerkr of Espeu, recorded by Kroeber

The Flood: There used to be a settlement at Sigwets just north of Orekw. Then it happened that there almost came to be no people (left in the world) on account of (what happened at) this settlement. For an old man and his brother went into the sweathouse to sleep. But a man was outside, and when they slept, he went in and tied their hair together. Then he went out and shouted, "They have come! Somebody will be killed! They are going to fight!

Figure 7. Traditional Woodpecker-crest headbands.

Then the ocean began to turn rough (from the anger of the old men). A breaker came over the settlement (of Sigwets), washed the whole of it away, and drowned everyone. Then all the people of Orekw ran off to the top of the hill, wearing their woodpecker-crest headbands: they were afraid.

Then he at Orekw who knew the formula for the sacred sweathouse there ran to Oketo, for now the water was already all around Orekw. He looked into the sweathouse at Oketo. There was the one who knew that formula. He spoke to him, but that one did not answer. Four times he spoke to him. Then he said. "Were they drowned?" "Yes, I saw them drown," said he of Orekw, "but I am afraid the water will cover the whole land."

And now the breakers were already dashing against one side of that sweathouse (at Oketo). Then that one began to speak his formula in that sweathouse. He had to do it hastily; therefore he used old boards to make the fire. Then the ocean went down. *Yurok legend told by Tskerkr of Espeu, recorded by Kroeber*

This site is unique not only for its oral history of earthquakes and tsunamis but also for the close correlation of story and physical evidence of past tsunamis. In the 1980s, Deborah Carver began compiling North Coast Native American oral histories related to earthquakes and tsunamis. A careful analysis of Tskerkr's story suggested that the water height above Sigwets was about 19 m (62 ft). Ida's story from just north of Redwood Creek suggested a water height of 18 m (59 ft). At the same time, her husband HSU Geology Professor Gary Carver was conducting paleoseismology research looking for physical evidence of past earthquakes and tsunamis. Cores taken at the mouth of the Orick Valley record tsunami sand deposits.

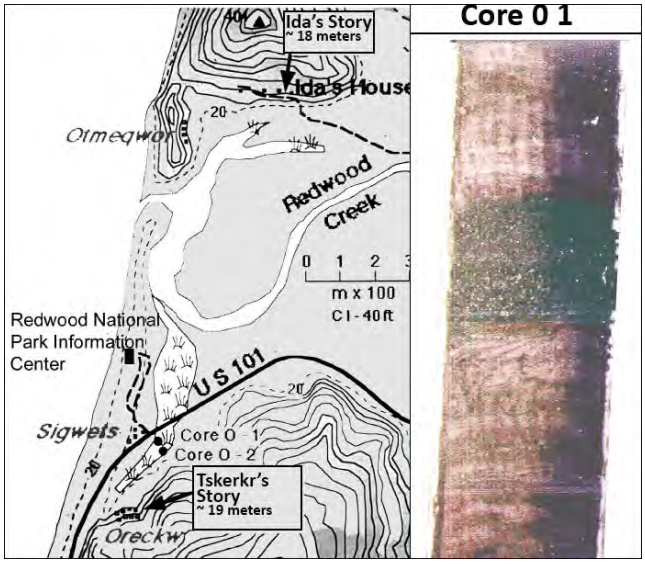


Figure 8. Left map shows location of Tskerkr's and Ida's stories and core sites. Core on the right shows tsunami sand deposit.

From the Redwood National Park Information Center, we drive north on U.S. Highway 101 to Lagoon Creek in the park.

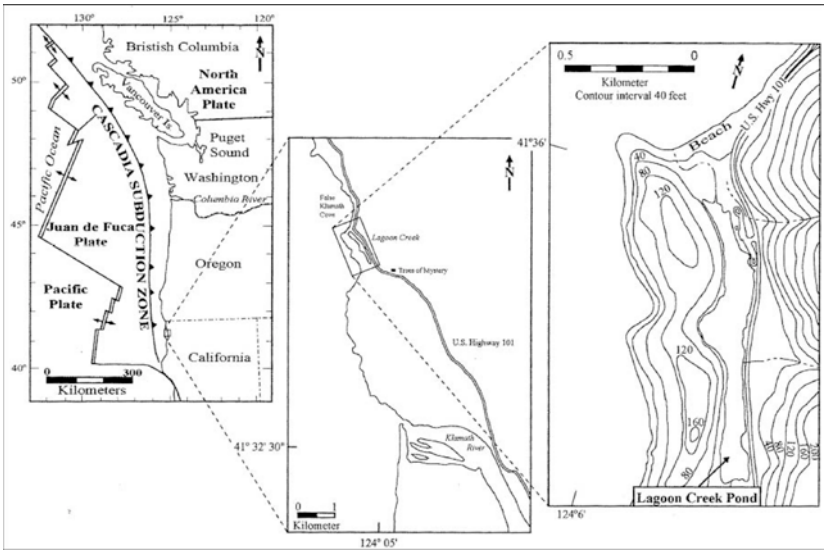
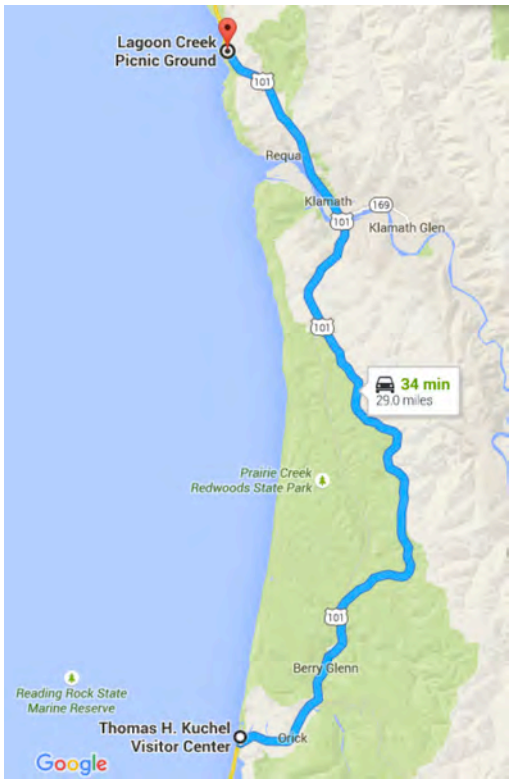


Figure 11. Location of Lagoon Creek.



STOP 3: Lagoon Creek

Lagoon Creek is likely the remnant channel of Wilson Creek that flowed to the south and drained into the Klamath River before coastal erosion cut off this reach and isolated it. The placid pond is blocked from the ocean by a 5 meter (over 16 ft) sand berm that was a mill site in the early 20th century (Figure 10). It provides an ideal sediment trap to collect deposits from tsunamis large enough to overtop the berm. Two HSU geology masters students Carrie Garrison-Laney and Hans Abramson Ward working under Dr. Gary Carver examined the stratigraphy and micropaleontology from 27 cores retrieved from the pond in 1987 (Figure 11).

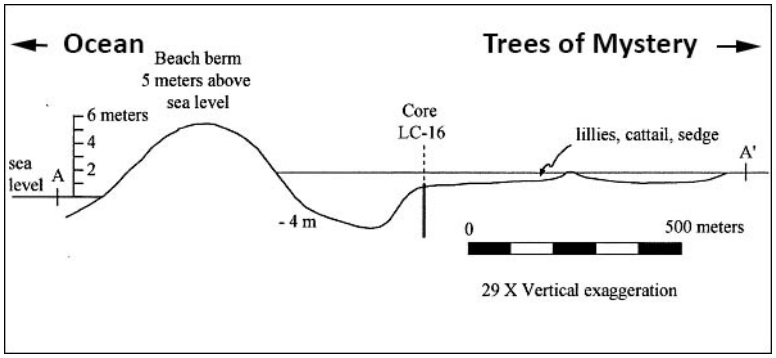


Figure 10. Profile of the Lagoon Creek channel, note vertical exaggeration. Core LC-16 was the site of the most detailed micropaleontology analysis. After C. Garrison-Laney, 1989

They found evidence for six tsunami events in the past 3500 years:

Event	Age	Inland extent (meters)
Y	315 BP* (1700)	870
W	~1100 years BP	1130
U	~ 1300 years BP	1060
S	~ 1600 years BP	1130
N	~ 2500 years BP	1100
L	~ 3200 years BP	>625

**Before Present*

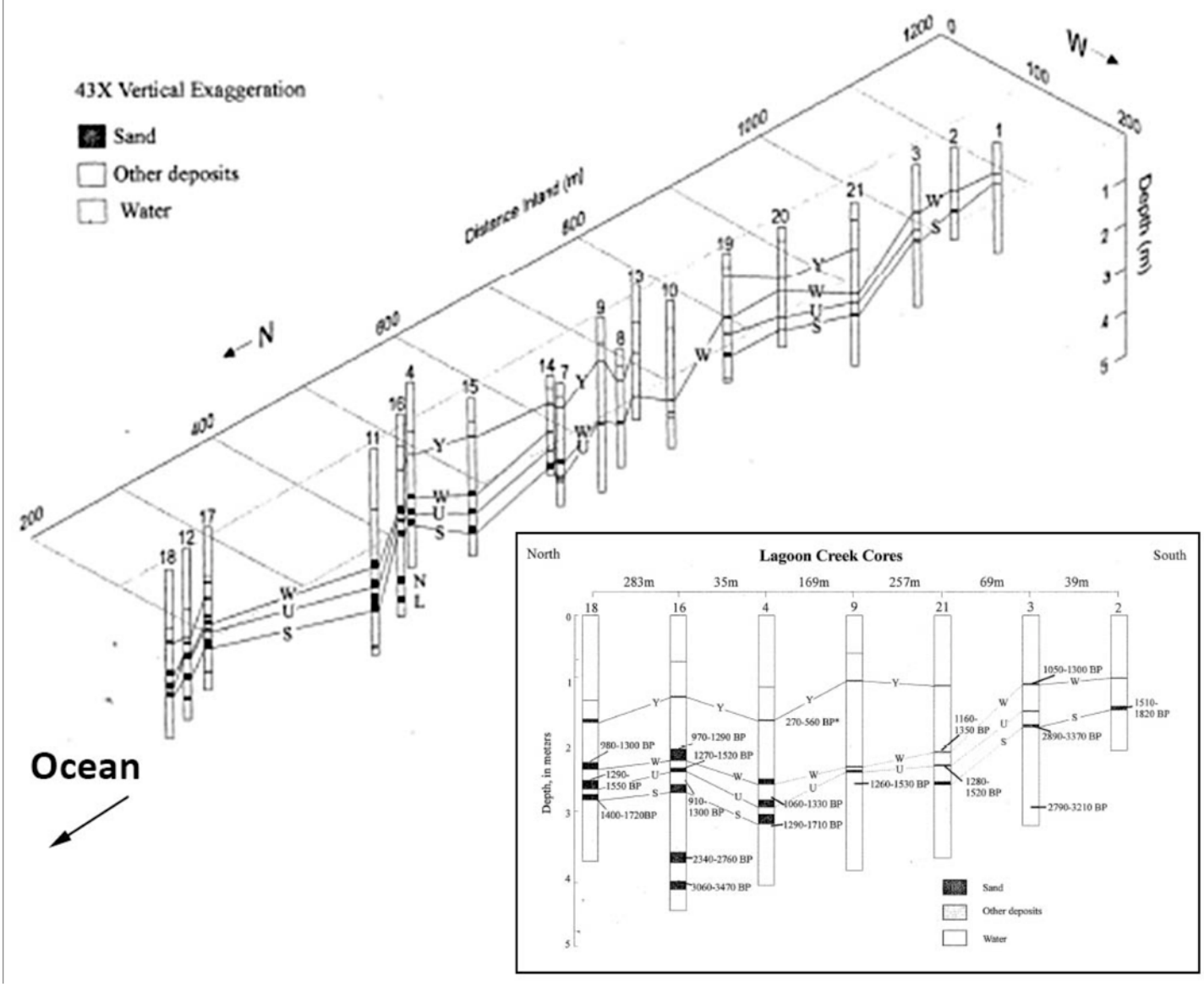


Figure 11. Core locations in Lagoon Creek. The coast is to the left. The black units are identified tsunami sand units and the letters correspond to the age of the unit inferred from stratigraphic position and radiocarbon dating. Three sand units (W, U, S) are observed in almost every core and are interpreted as more robust tsunamis than units only observed closer to the coast. After H. Abramson 1989.

The 5-meter berm appears to effectively protect Lagoon Creek from large tsunamis generated by distant tsunamis as there is no evidence of the 1964 tsunami in this location and all of the sand units correlate with identified Cascadia tsunamis from Oregon, Washington and British Columbia. One of the conclusions of the studies at this site is that not all Cascadia tsunamis are equal in size. The most recent Cascadia event corresponds to unit Y. It can be traced about midway through the lagoon but is not as extensive as units W, U, and S (1100, 1300, 1600 B.P.). Paleoseismology studies in Oregon also support this interpretation.

We also examine a gouge core pulled from a site near the open coast just south of Crescent City. This is near the location of the core you examined on campus. Unlike Lagoon Creek, the Crescent Beach site is exposed to the coast and has been impacted by large distant tsunamis as well as local tsunamis from the Cascadia subduction zone (Figure 12).

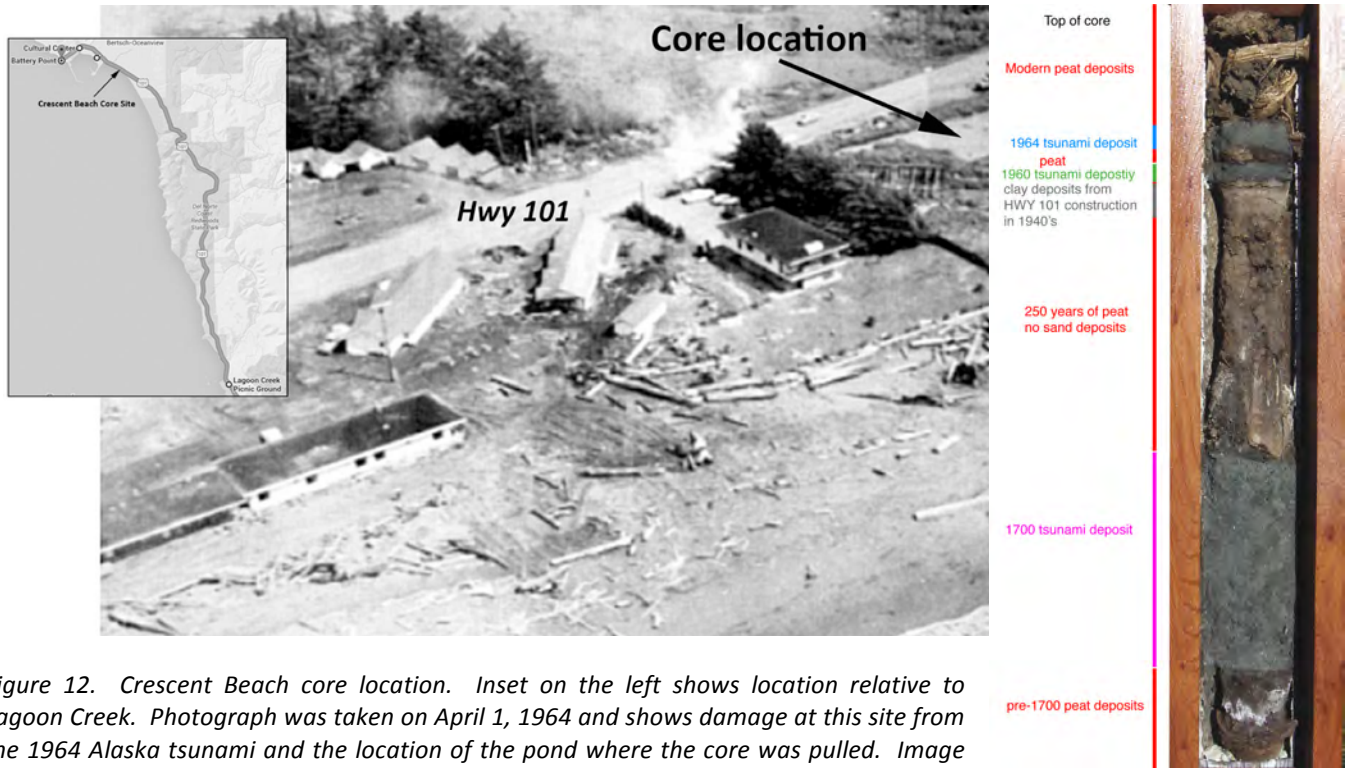
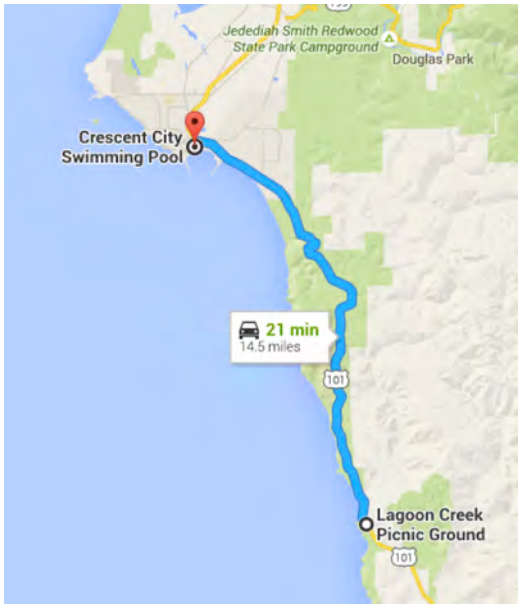


Figure 12. Crescent Beach core location. Inset on the left shows location relative to Lagoon Creek. Photograph was taken on April 1, 1964 and shows damage at this site from the 1964 Alaska tsunami and the location of the pond where the core was pulled. Image on the right shows the core you looked at on campus.

From Lagoon Creek, we continue north on U.S. Highway 101 to Crescent City. Turn left at Front Street to Crescent City's Beach Front Park and Swimming Pool next to the Crescent City Cultural Center for our lunch stop.

The Beach Front Park was part of the Army Corps of Engineers post 1964 tsunami reconstruction. The entire beach area south of Front Street was elevated about seven feet. There are no residences now permitted in this area now – it is zoned for recreational use only.



Stop 4: Crescent City Tsunami Walk

The 1964 tsunami is the most significant historic tsunami event to impact the west coast of the United States and Canada in the past 200 years of European settlement. On March 27, 1964 a magnitude 9.2 earthquake struck the Prince William Sound area of Alaska at 5:36 PM Alaska Standard Time (7:36 PM PST). This was the second largest earthquake ever recorded with modern seismic instruments; only the 1960 M 9.5 Chilean earthquake was larger. The fault rupture extended about 500 miles in length and 150 miles in width and uplifted some regions over 30 feet while other areas sank as much as 7 feet. Tsunamis were generated both by the fault rupture and also by numerous large submarine landslides. Impacts were greatest in Alaska where the highest tsunami water levels exceeded 200 feet in Shoup Bay in the Valdez inlet. Of the 115 deaths in Alaska attributed to the earthquake, over 90% (106) were caused by the tsunami.

The tsunami traveled outward from the source region at speed of about 415 miles per hour causing damage along the Southeast Alaska, British Colombia, Washington and Oregon Coasts. At 11:08 PM PST, about 3 1/2 hours after the earthquake, the California Disaster Office issued an emergency bulletin to all coastal police and local disaster office officials stating that a "tidal wave" was probable but not confirmed. At 11:50 PM a similar bulletin issued by the State Civil Defense Office estimated the arrival time of the first wave as 12:00 AM. These bulletins were received by the Del Norte County Sheriff's Department and the sheriff sent deputies to the low waterfront areas to tell people that a wave was expected. He did not order an evacuation and the deputies had not completed the door-to-door notification when the first wave arrived at 11:52 PM. Anecdotal reports suggest that most people had left the waterfront area before the first wave arrived.

The first wave caused modest flooding and deposited some debris on the beach and Front Street in the Downtown Crescent City area and near Citizens Dock. Its elevation is estimated at 14.5 feet above Mean Lower Low Water (MLLW) or about 8 feet above the ambient tide level (a high tide of about 6 feet at the time of the first wave arrival). After the first wave, the harbor emptied completely before the arrival of a second, smaller wave at 12:20 AM on March 28. This wave crested at 4 to 6 feet above the ambient tide and did not reach Front Street. Some people reentered the waterfront area, assuming the worst of the event had past. Others, hearing about the wave damage, came to sightsee.

There is some discrepancy about the arrival time and size of the later waves as the tide gage in the Crescent City harbor ceased recording a little after 1 AM. Eyewitnesses generally agreed that the third and fourth waves were both larger than the first wave, the third arriving at about 1:20 AM and the fourth and largest at 1:45 AM. From measurements of high water marks on land, it reached a height of about 22 feet above MLLW or nearly 16 feet above the ambient tide. By the time of the 4th wave, the sheriff had decided to close off the entire waterfront district to keep out sightseers and potential looters, but a general alarm was not issued until after the largest wave struck. Almost all of the damage was caused by this wave – 10 deaths, 54 homes destroyed and an additional 37 damaged forcing 150 people to seek shelter elsewhere. One hundred seventy nine businesses in a 29-block area were affected, 42 of which were totally destroyed. The cost (in 1964 dollars) is estimated at about $15 million. A contributing factor to the high loss of structures was that most buildings not secured to foundations and were highly vulnerable to being lifted by the water and displaced.

Elsewhere along the Northern California Coast, the impacts were not as great. One death was reported in the Klamath River and there was $4,000 in damage to piers and docks. The tsunami was observed at least 1.5 miles upstream of the Klamath mouth. In Humboldt County, the tsunami caused water to breach a ten-foot seawall at the Eureka Boat Basin and rise eight feet into the street.

Humboldt Bay was filled with logs and debris and nine changes in tidal height were reported over the night causing high current velocities within the bay. Fourteen-knot currents were reported in the channel opposite the Coast Guard Stations. At Trinidad, water was reported to have reached 16 feet above MLLW or 10 feet above the tidal height at the time of the tsunami. Eyewitness accounts reported significant flooding in Fairhaven on the Samoa Peninsula. In Mendocino County, the tsunami reached heights of at least 6 feet and damaged or sank over 120 boats on the Noyo River. One death was attributed to the tsunami in Bodega Bay over 13 hours after the first wave arrived. The tsunami caused seiching (oscillations) in San Francisco Bay and caused damage to boats and docks estimated at $1 million. Some damage to boats and docks was reported as far south as Santa Monica and Los Angeles.

Lessons from the 1964 tsunami

The most important lesson from the 1964 tsunami was that failure to evacuate kills people. People who were out of the inundation zone survived while many of those in the area of flooding did not. Impacts were exacerbated by later waves being much larger than the first. A study conducted by the Disaster Research Center at Ohio State University in 1964 examined the problems with the warning notification and evacuation and concluded:

- The first tsunami warning bulletins was received in Crescent City only 50 minutes before the expected arrival of the first wave. The time was insufficient for a controlled evacuation.
- The wording of the tsunami bulletins may have confused local officials. The bulletins warned of a "probable" but "unconfirmed" wave.
- In 1957, the Sheriff's Office had evacuated the downtown area and no significant wave had occurred. There were many recriminations that may have affected the response in 1964.
- The Del Norte Sheriff's Office only sent deputies to the water after the second bulletin arrived. They did not order an evacuation, but rather informed people that waves were possible. Past tsunami experiences may have also contributed to the losses. Tsunamis were not a new experience for Crescent City and the city had experienced some flooding from tsunamis in 1946, 1952, 1957 and 1960. The tsunami in 1960 was the most damaging in Crescent City's history and at the time may have set the standard for the "worst-case" event. The first waves in 1964 were very similar in impacts to 1960 and the second wave was smaller. It is not surprising that some people returned to the downtown area based on their previous experience.
- Wood-frame structures in the inundation zone were particularly vulnerable to damage because very few were secured to foundations and were easily floated by the water. Much of the damage was the result of floating debris – cars, logs, damaged structures – colliding with buildings.

What are the odds of another 1964 tsunami event?

Thirty-eight tsunamis have been observed or recorded on California's North Coast since 1855. All but four were distant tsunamis (the source was far away). Crescent City in Del Norte County has suffered more tsunami damage in the past 150 years than any other area of the US West coast outside of Alaska. Major damage occurred in the 1960 and 1964 distant tsunamis and significant wave activity was observed in 1946, 1952, and 1957. Looking only at the record from 1940 – 1970, one might conclude we are long overdue for another damaging distant tsunami. However our historic record is not long enough to make good probability estimates and distant tsunami studies from Oregon and California suggest that 1960 and 1964 type tsunamis might be uncommon events. So the short answer is that we do not know, but the potential damage is great enough that we need to be prepared.

Are we better prepared today?

There is no question that the US Tsunami Warning system has significantly improved since 1964. Local emergency managers and public safety officials routinely receive bulletins from potentially tsunami-producing earthquakes in the Pacific Ocean within 15 minutes of their occurrence. For earthquakes originating in Alaska, the time is even shorter. This information is rapidly disseminated on NOAA Weather Radio and through the Emergency Alert Radio system. In 1996, Congress provided funding for the National Tsunami Hazard Mitigation Program. As a result of this program, about 40 deep ocean sensors (the DART system) have been deployed within the Pacific to record tsunamis in real time and provide information on the damage potential of a tsunami. The program has also supported tsunami inundation modeling and mitigation programs in all coastal states and territories. Inundation maps are now available for most coastal communities, and tsunami signs are posted in many west coast tsunami zones. The bottom line? We should be in much better shape for the next distant tsunami like 1964. But we have got much work to do to prepare for the next local tsunami from the Cascadia subduction zone.

<u>Crescent City Tsunami Walk and 1964 tsunami impacts</u>

In 2014, as part of the 50-year commemoration of the 1964 tsunami, Crescent City developed a tsunami walk with kiosks explaining what had happened during the tsunami. We will visit most of the kiosks on a short walk around the Crescent City downtown area that was most impacted by the tsunamis (next page).

The Army Corps of Engineers was responsible for the redevelopment of the downtown area after the tsunami. Most of the structures within the 29-block area devastated by the tsunami were removed. Figure 13 is a snapshot of the changes wrought by the tsunami and post event rebuilding from the perspective looking east at 2nd and H Streets.

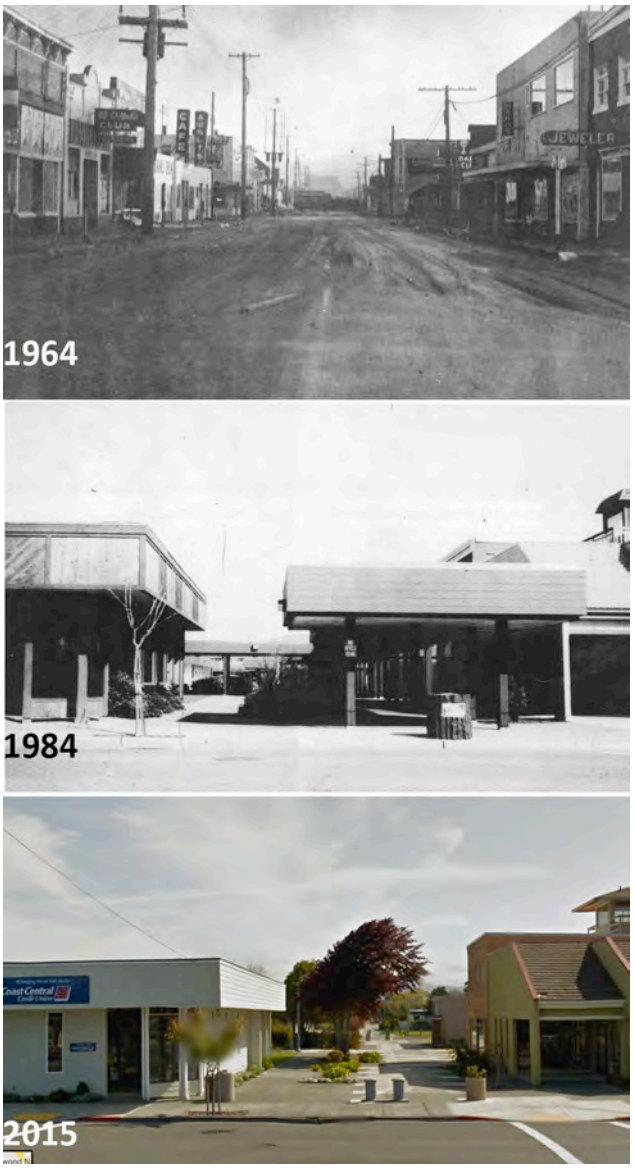


Figure 13. 2nd and H Street looking east. Top photo taken a few days after the tsunami shows the through going 2nd Street and the mixed commercial neighborhood before the tsunami. Twenty years later (in 1984) 2nd Street had been replaced by the Tsunami Landing promenade walk was nearly void of businesses. The promenade was removed in 2013.

1 Jetty Dolos and Tetrapod

Front Street, Below J Street

You'll find this behemoth located just east of the Cultural Center on Front Street.

These 40-ton "jacks" were built on-site to bolster the harbor breakwaters. A 25-ton Tetrapod was pushed off its display pad during the '64 Tsunami.

2 Elk Creek Bridge

Just East of Dolos on Coastal Trail

Walk southeast on the paved path to the newly built Elk Creek foot bridge.

This is where the worst loss of life happened when five people drowned while receding tsunami waters pulled their boat under the highway trapping them.

3 Tsunami History Kiosk

Second & K Streets

Head back west, then north up K Street to Second Street.

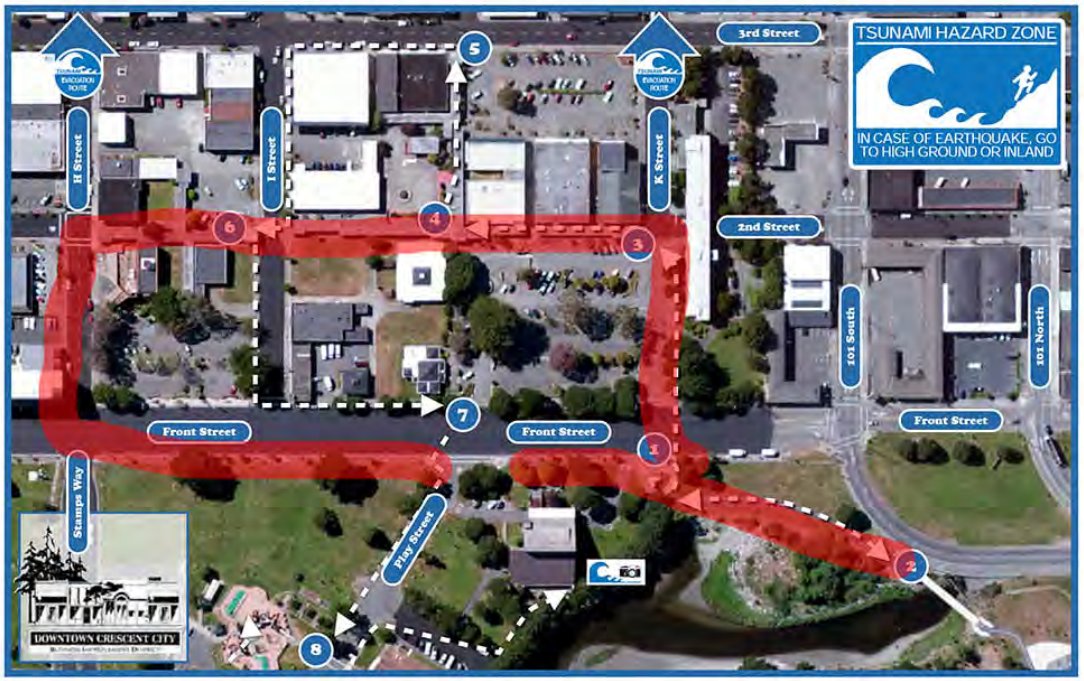
You'll learn how the offshore topography makes this area a tsunami magnet that over the years has ravaged both the Downtown and Harbor, which was heavily damaged in 2011.

4 Memorial Fountain

Tsunami Plaza

Take a short walk east along what used to be 2nd Street to Tsunami Plaza, one of the new wide-open spaces built after the 1964 tsunami.

This fountain was erected by the citizens of Crescent City as a remembrance to the eleven people who lost their lives. You'll learn the story of how citizens rebuilt their town and will never forget those they lost.



5 Historical Downtown

Third & J Streets

Head north through modern Downtown, on what used to be J Street, up to 3rd & J Streets for this kiosk.

Before the 1964 tsunami, Downtown Crescent City was a thriving area of over 250 shops, motels, cafes and bars that catered to fishermen and lumberjacks. Today's views are very different because nearly 29 blocks were wiped away that night by the tsunami.

6 Mural & KPOD Building

Second & I Streets

Head west on Third Street and down I Street to see buildings that survived the '64 Tsunami and a mural that immortalizes it.

Bill Stamps broadcast on KPOD radio that night until power was knocked out and he barely escaped with his life.

7 A Tsunami Resistant Town

Front Street and J Street

Head south down to Front Street and head east to the kiosk.

The Downtown architecture after the '64 tsunami reflects the ideas for minimizing damage of any future tsunami debris with deflecting sea walls and wide open spaces to slow surges.

8 Beachfront Park Buffer Zone

Kids Town, Beachfront Park, Pool

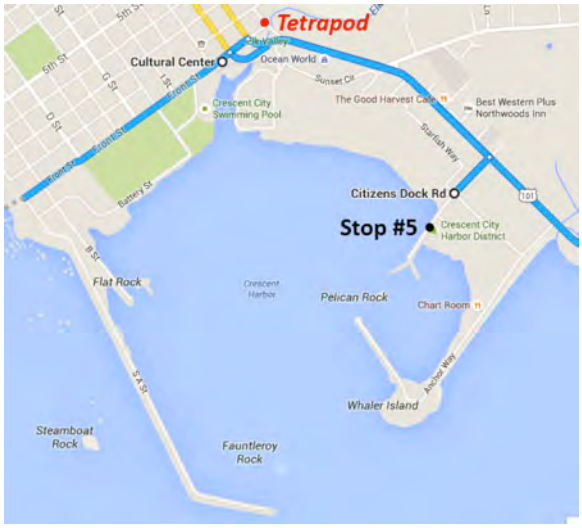
Crossing south across Front Street, take the sidewalk south to the Kids Town entrance across from Fred Endert Municipal Pool.

While rebuilding, tsunami debris was used to fill in the park to raise it 10 feet higher and build the surrounding sea walls 16 feet high.

Coming Soon! - The life-size 1964 Crescent City Tsunami Wave Mural on the east wall of the Cultural Center, which was officially 20.7 feet high!

After the Crescent City Tsunami Walk, we take the short drive to Crescent Harbor. Time permitting, we will briefly look at the famous tetrapod displaced by the 1964 tsunami.

Figure 14. The tetrapod at the corner of N and Front Street was displaced about 3.5 meters in the 1964 tsunami. The photo of the right was taken the day after the tsunami and shows the culprit – the log whose impact provided the necessary force to move the 25-ton object.



Stop #5: Citizen's Dock and Crescent Harbor

This area bore the brunt of the 1964 tsunami. It also experienced moderate to major damage in four other tsunamis.

Damaging Tsunamis in the Crescent City Area

November 4, 1952 Source: Kamchatka, Russia, strong currents in harbor capsized 4 boats

May 23, 1960 Source: Southern Chile, flooding at Citizens Dock and to second street. $30,000 in damages.

March 28, 1964 Source: Prince William Sound, Alaska; 29 blocks in Crescent City flooded, 11 deaths in Del Norte County, $17 million in damages.

November 15, 2006 Source: Kuril Island north of Japan, strong currents destroyed/damaged docks in boat basin, ~$20 million in replacement costs.

March 11, 2011 Source: Japan, strong currents destroyed what remained of the boat basin ~ an additional $15 - $20 million in damages

Crescent City is well known in the tsunami world as a site that amplifies the tsunami – at least for tsunamis coming from far away. There are five reasons why Crescent City is a "tsunami magnet":

1. Location on the coast. Crescent City juts out into the Pacific Ocean. It is the second most western point in California, losing to Cape Mendocino by only 19 km (12 mi). Unlike Cape Mendocino, Crescent City is low-lying and the only relatively populated exposed community north of Mendocino County. The populated areas of Humboldt County are protected by the spits and Humboldt Bay.

2. The shape of the Pacific sea floor offshore of Humboldt and Del Norte Counties. Look at a Google Earth image showing Humboldt and Del Norte Counties. You should be struck by the unusual sea floor bathymetry (depth to the sea floor) off of our coast. Zoom out a bit more and you will see a giant scar

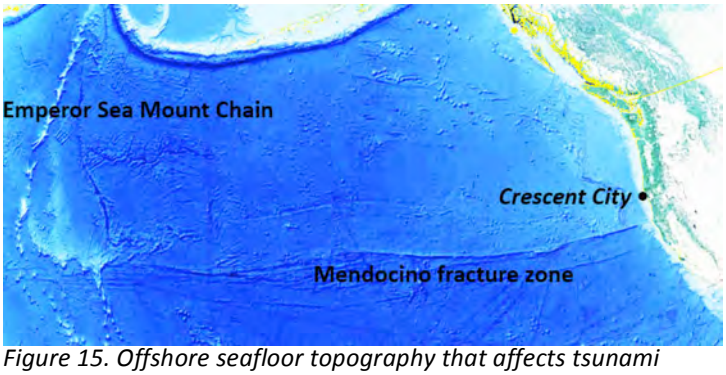


Figure 15. Offshore seafloor topography that affects tsunami amplitudes on California's North Coast.

stretching west from Cape Mendocino over 4000 km (2500 mi) into the Pacific Ocean. This is the Mendocino Fracture Zone - created by millennia of plate motions.

The result is that the Pacific Ocean to the north of the fracture zone is a little bit shallower than to the south. This difference becomes most extreme just off Cape Mendocino, where the escarpment (known as the Gorda Escarpment) reaches more than 1000 m (3000 ft). Tsunami speed is related to the depth of the sea floor. Tsunamis travel faster in deep water. A tsunami traveling to the south of the fracture zone is moving faster and to the north more slowly. Along the Humboldt and Del Norte coasts, the shallow water slows the tsunami, which causes more water to build up behind the wave front. By the time a tsunami hits the US west coast, it will be a little bit larger along the north coasts than to the south. The effect is probably not large - but even a 5 or 10% difference can be significant in large tsunamis. The effect is likely larger on the Humboldt than on the Del Norte coast - but Humboldt does not have the Crescent City's exposure (reason 1).

There is a second effect of the sea floor shape - Going a little further west from the end of the Mendocino fracture zone, you can see a chain of sea mounts extending to the north. This is the Emperor Sea Mount Chain and its orientation and shape tends to focus tsunami energy from the northwestern Pacific Ocean (Japan, Kuril Islands, Kamchatka) toward our coast.

3. The shape of the continental shelf and the coast off the Humboldt and Del Norte coast. If you look at a map of California's North Coast, note the curvature of the Humboldt and Del Norte coast line and the relatively flat, smooth appearance of the shelf. The shelf is actually slightly bowl shaped. Tsunami energy hitting this coast excites secondary oscillations in this large gentle "bowl" - rattling around for days when a large tsunami strikes. These secondary waves add to the continuing wave train of the primary tsunami resulting in constructive interference. The result is that the largest surges at Crescent City always arrive at least a few hours after the first and the signal lasts a long time. The 2011 tsunami could be clearly seen on the Crescent City tide gauge for at least 6 days. The same effect occurs on the Humboldt coast too - but the only tide gauge is inside Humboldt Bay, which is very shallow and dampens tsunami energy quickly.

4. The shape of Crescent Harbor. The gentle, relatively open south-facing harbor also traps tsunami energy. Half Moon Bay has a similar behavior - but does not get the added oomph of points 1 - 3 above. The bay does two things: it focuses the tsunami into the bay and sets up another set of secondary oscillations which further interferes with the primary tsunami and the shelf oscillations.

5. The design of the Small Boat Basin. The small boat basin to the north of us was built as part of the Crescent City renovations after the 1964 tsunami. It was intended to protect the fishing fleet from storm waves which can become quite large in the relatively unsheltered open bay. It does a good job of protecting boats from the relatively short period wind waves and swells caused by storms. But long period tsunami waves are first focused into the natural harbor and then further squeezed into the narrow entrance of the basin. Tsunami modeling has demonstrated a six-fold increase in the water speed inside the boat basin

Figure 16. Citizens Dock on April 1, 1964 after the tsunami. The tide gauge was located near the end of the badly damaged Lumber Dock.

compared to the larger outer bay. In addition, the relatively solid walls of the boat basin means that wave energy is reflected with little dissipation in the basin.

A tide gauge was installed on Citizens Dock in 1933 (Figure 16). The original instrument sat near the end of the Lumber dock – the northern fork of the dock. Tide gauges provide a record of water level in as a function of time. In addition to measuring the tidal fluctuation, they also record tsunamis and storm surges. Since 1933, the gauge at Crescent City has recorded 38 tsunamis. Figure 17 shows four Crescent City marigrams. All four show typical characteristics of Crescent City tsunamis – long duration and the largest amplitude signal occurring hours after the initial wave.

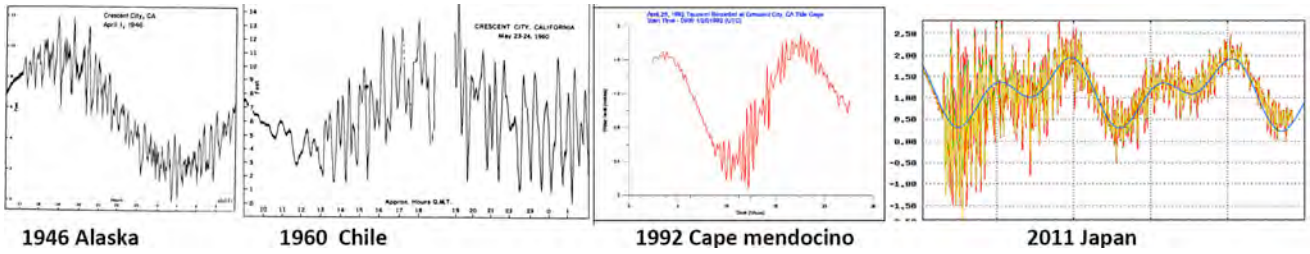


Figure 17. Marigrams recorded at Crescent City. Only the 1992 tsunami was produced by a nearby earthquake.

The largest tsunami ever recorded at Crescent City was from the 1964 Alaska tsunami. The first tsunami wave arrived at 11:50 p.m. PST and arrived at high tide, with the water height reaching 15.5 feet above Mean Lower Low Water (MLLW). This first surge caused flooding as far as Front Street – nearly the same as the peak inundation produced only four years earlier from the 1960 Chilean tsunami. The second wave arrived a half hour later and was smaller. Water heights were low for over a half hour and many residents thought the tsunami was over and returned to the flooded area. Unfortunately, the third surge was larger than the previous waves and overtopped the dock, knocking over the tide gauge instrument housing. Eyewitness accounts agree that there were four significant waves and that the third and fourth were the largest. The maximum water, inferred from the peak debris line, is about 6.7 m (22 ft) above MLLW.

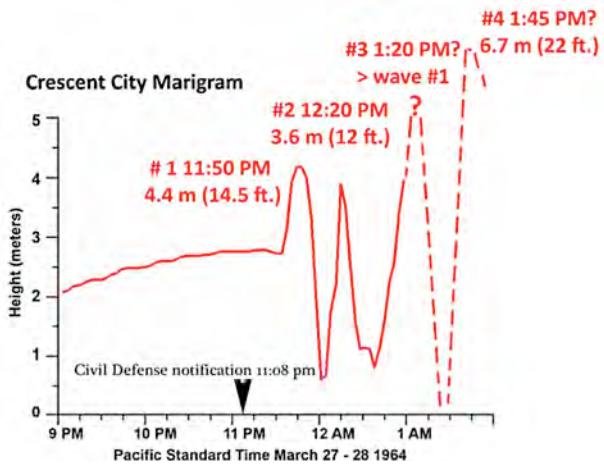
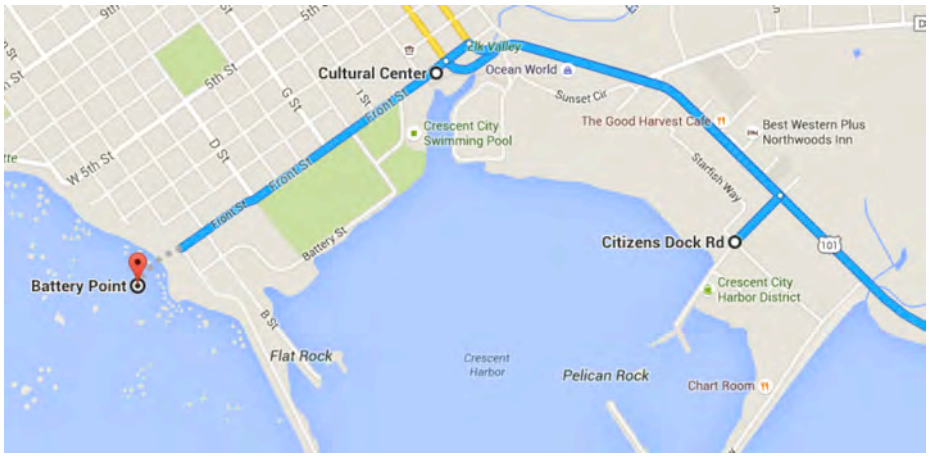


Figure 18. Crescent City marigram for the 1964 Alaska tsunami. Solid lines are the actual recording. The instrument was knocked over as the third surge arrived. The dashed lines are estimates based on eyewitness accounts.

From Crescent Harbor, we drive along Front Street to the parking lot next to Battery Point Lighthouse and walk the short distance across the isthmus to the island. Access to the lighthouse is only possible at low to moderately low tides.



Stop #6: Battery Point Lighthouse

Figure 19. Battery Point Lighthouse.

Battery Point Lighthouse, built in 1856, is located just west of the Crescent City breakwater. Battery Point Island, elevation 32 feet, got its name from a "battery" of guns–three brass cannons salvaged from the 1855 wreck of the America–which were place on a point of land near the island. The parking area across from the island was a Tolowa village. Before the Crescent City pier was built, the Point was on a peninsula, connected to the mainland by sand. Passengers and freight were ferried between ships and the shore in small boats. The lighthouse was built to guide navigation through the dangerous, rocky entrance to the harbor. After the outer breakwater was built, sand no longer replenished the connection and the Point became an island at all times except low tide. The lighthouse beacon, 75 feet above sea level, can be seen 14 miles offshore. It remained in service until 1965 when the Coast Guard ceased to use the station. In 1982, the lighthouse was reactivated as a Private Aid to Navigation, and is supported by the Del Norte Historical Society.

In March, 1964, Peggy and Clarence Coons were the resident curators of the lighthouse. Peggy Coons wrote the following description of the tsunami.

CRESCENT CITY'S DESTRUCTIVE HORROR OF 1964 (THE VIEW OF THE TIDAL WAVE FROM THE LIGHTHOUSE AS DESCRIBED BY PEGGY COONS, CURATOR OF BATTERY POINT LIGHT HOUSE IN 1964)

-from the Del Norte Historical Society files.

Good Friday, March 27th, 1964, the morning was mild. The tradewinds that prevail along the Pacific Coast had subsided. Little did I realize, as my husband Roxey and I went about our chores at the lighthouse, that before the next day had dawned high on Battery Island, we would watch four waves play havoc with the town and its people. Smashing the city's business center along with some of the beach front homes in Crescent City, CA, and we would have a spectacular view of the whole performance. And as curators here

at the lighthouse we would be called on by friends and tourists alike to relive this one night of horror almost everyday since.

Perhaps I should stop to explain Battery Island, three hundred yards from the mainland, is solid rock at the base and about three quarters of an acre, fifty-eight feet at the highest point near the flagpole. The lighthouse, completed in 1856, is 74 feet above mean sea level. The only access to this Historical Monument is walking across the ocean floor at low tide.

We spent the early part of the day planting a garden. Friday was our shore leave, so we crossed to the mainland at three o'clock to shop for Easter. Late that evening we struggled back across the rocky ocean floor with our supplies and stopped to rest before climbing another two hundred yards to the lighthouse. Exhausted, we turned in shortly after nine o'clock unaware an earthquake and tidal wave had devastated Alaska. We might have slept through the whole thing if I hadn't gotten up to go to the bathroom a little before midnight. I stood at the window, a full moon shining on the water below me. Somehow the first moment I saw the ocean I sensed something was wrong, for all the rocks around the island had disappeared. They were covered with water. I realized it was almost time for high tide, but the rocks are always visible even in the severest of storms. Suddenly I became alarmed and called Roxey. We quickly slipped on some clothes, rushed down the stairs, and grabbed our jackets as we ran outside.

The air was still, the sky had an unusual brightness about it. It was light as day. The water shimmering in the moonlight was high over the outer breakwater. We headed for the highest point overlooking the town. The first wave was just reaching the town. Giant logs, trees and other debris were pitching and churning high on the crest of the water as it raced into the city. "My God, no!" I cried, "It will flood the town." As the impact began, the loud blast of breaking glass and splintering wood reached us, buildings crumpled, cars overturned, some smashed through plate glass windows, while the water plowed down the streets. Within minutes the water came back just as fast as it had gone in, bringing all manner of things with it. It drained away with terrific speed. The whole beach front was strewn with logs, cars, buildings, trash of every description. Some of the fishing boats were tossed high on the land, others drifted to sea. A few cars and two small buildings that were swept off Citizen's Dock floated away with the water. The water was gone. We could see it piling up a half mile or more beyond the end of the outer breakwater, higher and higher as the minutes passed.

We stood there stunned with fright for we knew there was no way out of here if the water came this high. The light house, serene in the moonlight, had been battered with severe storms for over a century: could it protect us now? We have lived on the island since 1962 and watched the storms come and go, but this was unlike anything we had ever experienced. The light flashed in the tower. We knew we would have to notify the Coast Guard if there was any failure or discrepancy in it. I don't know how long we stood there for we were just too frightened to move, when the second wave churned swiftly by us, gobbling everything in its wake. It picked up all the ruins along the beachfront and shoved them right back into town. It didn't seem as large as the first one to us, but it caused considerable damage. Some of the lights faded out along Front Street. As the backflow began we raced frantically around the place, watching the water drain from the bay. We glanced at the tower: the light was still flashing.

We watched the Coast Guard Cutter, a big lumber tug, and some of the fishing boats that had received warning and left the harbor riding the tides a good three miles or more off shore. We were getting more frightened now, for the water had receded farther out than before. We knew it had to come back, but when? We screamed at one another in our fright, wondering if it would ever stop, for there was an ominous stillness about it, warning us of more to come.

As the third wave raced swiftly by us, it was much larger than the second, a horrifying thing, crushing everything in it's path. When it reached the south end of town, sparks started flying in the air, igniting a

fire. It spread rapidly, lighting up the water and sky around the bay. All of the lights faded out along the 101 highway.

The water withdrew suddenly, as though someone had pulled the plug out of the basin. The water was here, then gone. We ran around the lighthouse again wondering if we were safe. We kept anticipating something more violent would happen, for the water had receded far out, three fourths of a mile or more beyond the end of the outer breakwater. We were looking down as though from a high mountain into a black abyss of rock, reefs, and shoals, never exposed even at the lowest of tides. A vast labyrinth of caves, basins and pits undreamed of in the wildest of fantasy. In the distance a dark wall of water was building up rapidly, so the Coast Guard cutter, the lumber tug, and small craft appeared to be riding high above it, with a constant flashing of white at the edge, as the water kept boiling and seething, caught in the rays of the moonlight.

The basin was dry. At Citizen's Dock the large lumber barge, loaded with millions of board feet of lumber, was sucked down in the bay. The fishing boats still in the small craft harbor, were pulled down on the floor of the ocean. We clung to one another, asking God to have mercy on us. We prayed for the town and its people. We realized the water would return with more destruction to follow. We kept straining ourselves trying to visualize what would happen next, while the water piled higher and higher in the distance.

Suddenly there it was, a mammoth wall of water barreling in toward us, a terrifying mass of destruction, stretching from the floor of the ocean upwards: it looked much higher than the island, black in the moonlight. Roxey shouted, "Let's head for the tower." It was too late. As we turned toward the tower, he yelled, "Look out!" We both ducked. It struck, split and swirled around both sides of the island with such speed we felt like we were sailing right along with it. It took several minutes for us to realize the island hadn't moved. It crashed the shore, picking up the driftwood logs and other debris lodged in our roadway and along the beachfront. It looked as though it would push them on the pavement at the end of A street leading past the Seaside Hospital. Instead it shoved them around the bank and over the end of the outer breakwater through Dutton's Lumber Yard it tossed big bundles of lumber, some splitting up with planks like matchsticks flying in the air, while others sailed gracefully away. The water overflowing Dutton's Dock was high above it. At Citizen's Dock, the large lumber barge, loaded with lumber came up and sat on top of the dock. The dock humped up, then relaxed right off its pilings. The fish storage houses, on the fish wing, were dancing around in the fury. The fishing boats still at their moorings were bobbing around like corks. Some sank right where they were while others flew onto the beach, while others came out, careened about and flew on the other side of the bay. One boat took off Elk Creek at the end of town as though someone was at the helm.

When the Tsunami assaulted the town it was like a violent explosion, a thunderous roar mingled with all the confusion. Everywhere we looked buildings, boats, lumber, everything was shifting around like crazy. The whole front of town moved, changing before our eyes. By this time the fire had raced across the water to the ruptured Texaco Bulk tanks: they started exploding one after the other. The whole sky lit up. It was fantastic.

As the tide turned it was sucking everything back with it: cars, buildings were moving seawards. The old covered bridge, from Sause Fish Dock, that had floated high on the land, came back to drop almost in place. Furniture, beds, mattresses, TVs, radios, clothing, bedding, and other objects were moving by us so fast we could barely discern what some of it was. A siren was blowing. There were lights now in the front of town or along Highway 101. The light in the tower continued to burn. The block on this end of town near the Seaside Hospital was unharmed. Across the bay the fire was till raging higher and higher as each tank exploded. Time passed quickly, for everywhere we looked was a shambles; houses, buildings, lumber, boats, all smashed or moved blocks from where they had been by the onrush of water.

The fifth wave rushed swiftly by us back into town. It just pushed things around. We could observe no noticeable damage this time, but off and on the rest of the night the water kept surging in and out and slopping around in the harbor. At daybreak we made coffee and fixed our breakfast, but we kept checking each change of the tide. We had never seen so many in our knowledge of the sea. The boats continue to ride the surf off shore, waiting for another big one. A fishing craft careening around in the harbor finally sank. The boat up Elk Creek had settled among the ruins of the new Olympic Pool. The cars along with the two small buildings, that were swept off the dock had faded from sight. Logs, boats, furniture along with the buildings all tossed helter skelter. The lumber from three big yards was tossed high on the land or floating in the water. Some of the landing and small craft floats were sailing away in a dizzy pattern.

Isolated on the island we watched the search begin along Elk Creek for the bodies of the victims. The demolition crews started clearing the streets and burning the debris along the beachfront and the 101 highway. The silent killer had left after taking its toll of life and property, but the vacant lots, the broken fish docks, along with abandoned fishing boat hulls still reminds us of the gruesome night the Tsunami destroyed 56 blocks of Crescent City, CA.

It still seems hard to believe that with all the salvage that floated by us out to sea, the only bit to reach the island was one spool of lavender thread.