stratigraphic evidence of paleoearthquakes and paleotsunami in mid- to late-Holocene sediments:

humboldt bay and lower eel river valley, southern cascadia subduction zone

October 22, 2005
Humboldt Friends of Geology
www.humboldtfog.org
Field Trip 4

Trip Leaders:
Tom Leroy
and
Jay Patton

Cascadia Geosciences Cooperative and Pacific Watershed Associates

Hookton Slough (Patton 2004)

Mad River Slough (Pritchard, 2004)

Swiss Hall (Witter and others, 2000)

North Spit (Leroy unpublished, 2005)

South Bay
Table Bluff
lower Eel River valley

North Spit (Leroy unpublished, 2005)
ACKNOWLEDGEMENTS

You can’t forget your roots, so to that end we must acknowledge the plethora of people who by their hard work and determination have helped bring us to our current understanding of the Holocene stratigraphy and tectonics of the Humboldt Bay region. First and foremost is Gary Carver. Gary, with an insatiable appetite for paleoseismology, has spearheaded the campaign to better understand the Holocene stratigraphy of the area and has played a role in almost every coring campaign to date. Both trip leaders have benefited from Gary’s active participation in their research projects. There is no doubt that Gary has slogged through more mud in Humboldt Bay than anybody (short of a few oyster fisherman and duck hunters. Many of Carver’s graduate students and colleagues have also made significant contributions to the understanding of the geologic processes operating in and around Humboldt Bay, they include, not in any particular order: Gordon Jacoby, Greg Vick, Dave Valentine, Chris Shivelle Manhart, Hans Abramson, Carolyn Garrison-Laney, Rob Witter, Harvey Kelsey, Eileen Hemphill Hailey, Mark Hemphill Hailey, Chad Pritchard, Bud Burke, and untold others. Pacific Gas and Electric and the USGS National Earthquake Hazard Reduction Program have both provided much needed funding to many of the projects we are reviewing in this guide book.

We would like to thank the following people and business for their contributions.

HSU, Department of Geology
Pacific Watershed Associates
Six Rivers Brewery

For continued support of non-profit geologic research that results in increased awareness to geologic hazard, please send contributions with checks made out to Jason R. Patton or Tom H. Leroy to:

Cascadia Geosciences Cooperative, c/o Jay Patton,
380 Beach Drive, Manila, CA 95521
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Active tectonics and large expanses of sheltered inter-tidal marsh make Humboldt Bay a unique location to study Holocene coastal processes. High regional erosion rates in conjunction with rising sea level and a myriad of active faults and folds make this coastal environment ripe for creative research in the field of paleoseismology. To that end, we think a summary of a few of the studies done in and around Humboldt Bay would be worthy of a Humboldt Friends of Geology (FOG) field trip.

This one day field trip will primarily review the marsh and Dune stratigraphy of the Humboldt Bay region. We will start in South Bay and review several locations where coring campaigns have provided information on the paleoseismolgy of the southern portion of Humboldt Bay. We will also discuss newly emerging evidence for elusive data regarding tsunami inundation in and around Humboldt Bay.

The field trip will then head to Mad River Slough, in Northern Humboldt Bay, to the review the paleoseismic evidence archived in this coastal estuary. Furthermore we will review the History of paleoseismic investigations in the Arcata Bay area and, as a group, collect a few gouge core samples and see if we can repeat published core logs of the area.

The final stop on our trip will review the coastal dune stratigraphy of the north spit of Humboldt Bay. We will discuss dune processes and geomorphic features of coastal dune fields. Furthermore, we will discuss evidence for tsunami inundation of the dune field and its implications.

Finally, for the comfort of those of you who were on the False Cape field trip, this trip will not involve any 700 vertical foot, 45 degree poison oak overgrown scrambles (although walking in mud and sand is not always easy).
Figure iii. Cascadia subduction zone map. Color represents elevation as shown in the legend (Haugerud, 1999). Approximate locations of plate boundaries shown include Cascadia subduction zone (Csz), Mendocino fault, San Andreas fault, Gorda rise, and Juan de Fuca ridge. Schematic cross section A-B shows Csz plate configuration. Inset map shows onshore and offshore mapped structures (Clarke and Carver, 1992). Source of inset map is from Sam Clarke (personal comm., 2000). Open circles locate paleoseismic investigations.
ITINERARY

(Stop 1) Table Bluff overlook – 8:00 AM

Review of the itinerary
Geologic overview and introduction
South Bay core site review and discussion
Eel River stratigraphy review and discussion

(Stop 2) Hookton Slough – 9:00 AM

Review the Holocene stratigraphy of Hookton slough
Discuss tsunami inundation in Humboldt Bay

(Stop 3) Mad River Slough – 11:00 AM

Review of Arcata Bay stratigraphy
Review of Mad River Slough stratigraphy
Collect 1 or 2 core samples and compare to reported stratigraphy

(Stop 4) North Spit dune field near Tyee city – 12:30 PM

Discuss Holocene dune stratigraphy of the North Spit
Observe anomalous gravel interstratified with dune deposits
Discuss the implications of the gravel being tsunami deposits

(Stop 5 – optional) Six Rivers Brewery – 2:30 PM (a huge benefactor of tsunami relief and education)

Overview and discussion
The Cascadia subduction zone is an approximately 1,200-kilometer convergent plate boundary that extends from northern California to Vancouver Island, Canada (Figure iii). The Juan de Fuca and Gorda plates are subducting eastwardly below the North American plate. Seismicity, crustal deformation, and geodesy provide evidence that the Cascadia subduction zone is locked and is capable of producing a great (magnitude greater than or equal to 8.5) earthquake (Heaton and Kanamori, 1984; McPherson, 1989; Clarke and Carver, 1992; Hyndman and Wang, 1995; Flück and others, 1997).

Globally, great earthquakes along subduction zones have caused damaging ground shaking, ground rupture by upper-plate crustal faults, liquefaction, turbidites, uplifted marine terraces, and tsunamis (Plafker, 1972; Adams, 1990; Clarke and Carver, 1992; Merritts, 1989; Clague and Bobrowsky, 1994; Satake and others, 1996). Based on buried soil stratigraphy correlated with radiocarbon age data using tree ring wiggle matching and with the inference of a single orphan tsunami in Japan being caused by a single great earthquake, the entire length of the Cascadia subduction zone from Canada to California ruptured in January, 1700 A.D. (Satake and others, 1996; Jacoby and others, 1997; Yamaguchi and others, 1997).

There has been no historic Cascadia subduction zone earthquake along its entire length, but paleoseismic evidence indicates multiple earthquake cycles have occurred along the Cascadia margin over the last 8,000 years (Atwater, 1987; Hemphill-Haley, 1995; Garrison-Laney, 1998; Abramson, 1998; Kelsey and others, 2002; Witter and others, 2003; Figure iii). Evidence for Cascadia subduction zone earthquakes also has been found in Humboldt Bay Holocene stratigraphy in the form of buried soils (Carver and Burke, 1988; Vick, 1988; Clarke and Carver, 1992; Manhart, 1992; Li, 1992; Valentine, 1992; Carver and others, 1998; Leroy, 1999; Witter and others, 2002).

Quaternary deformation around Humboldt Bay has been dominated by contractile deformation due to Gorda – North America plate convergence and from northward Mendocino triple junction migration transpression (Ogle, 1953; McPherson, 1989; Carver and others, 1992b; Smith and others, 1993, and Burger and others, 2002; Williams, 2003). The deformation front of the Cascadia subduction zone lies approximately 75 kilometers offshore of Humboldt Bay (Clarke and Carver, 1992). East of the offshore deformation front is an 85- to 100-kilometer wide fold-and-thrust belt in the accretionary prism, which comes onshore in the Humboldt Bay region (Carver and Burke 1988; Clarke and Carver, 1992; inset Figure iii). Splays of the onshore fold and thrust belt include the Little Salmon fault and the Mad River fault zones (Fig ii). Transpression from Mendocino triple junction migration extends northward to at least the Table Bluff anticline (Burger and others, 2002).
Evidence for Holocene onshore tectonic activity includes (1) earthquakes on upper-plate faults of the Little Salmon fault in Salmon Creek valley and the Mad River fault zone in McKinleyville and Blue Lake (Carver and Burke, 1988), (2) sudden uplift of sections of the coast at Clam Beach (Figure ii) and Cape Mendocino (Figure iii; Clarke and Carver, 1992; Merritts, 1989; Stein and others, 1993, Carver and McCalpin, 1996), and (3) sudden subsidence along margins of Humboldt Bay and Eel River valley (Vick, 1988; Clarke and Carver, 1992; Li, 1992; Manhart, 1992; Valentine, 1992).

THE SOUTH BAY CORE SITE

Carver, Abramson, Garrison-Laney and Leroy (1998)

The South Bay core transect was conducted by Carver, Abramson, Garrison-Laney, and Leroy in 1998 as part of an investigation of paleotsunami evidence along the north coast of California for the Pacific Gas & Electric company. The South Bay core site was the most southerly study site of the project and the only site in Humboldt Bay to archive tsunami deposits. As we will see today, subsequent to this study, further tsunami deposits have been found in Southern Humboldt Bay.

The South Bay core transect is located in the south west corner of Humboldt Bay, on the eastern margin of the south spit where it abuts Table Bluff (Figure 1-1). The transect consisted of 10 vibra-cores located on the northern side of the currently breached levy running perpendicular to the spit.

The basic stratigraphy of the South Bay core transect is best summarized in the original report from Carver and others to PG&E:

“The stratigraphy at the South Bay field site consists of almost exclusively grey mud punctuated by several sand layers. Sand layers range from clean to muddy and from coarse to very fine-grained. Some sand layers contain grey mud rip up clasts. Some buried marsh soils occur, consisting primarily of slightly peaty mud to peaty mud with unidentifiable plant stems or roots. Locally, sand layers immediately overlie buried marsh soils in sharp contact.”
The South Bay core transect summary sheet below summarizes the pertinent conclusions of the study site.

**Paleoseismic and paleotsunami evidence at the South Bay core transect site**

**Vital Statistics**
Number of subsided surfaces = 2
Number of subsided surfaces with tsunami deposits on them = 2
Minimum number of tsunamis = 3

Approximate age of sediment at the base of the cores = 2000 BP
Core correlation = Difficult to moderate
Approximate age distribution of Tsunamis: Event 1 (320-0 BP), Event 2 (770-1220 BP), Event 3 (1500-1800 BP), Event 4 (1870-2320 BP)

**Paleoseismic evidence**
Lithologic evidence for coseismic subsidence
Diatom evidence for coseismic subsidence
Sand present on the subsided contact

**Tsunami Sand Layer Characteristics**
Sand layer thins inland
Rip up clasts
Sharp basal contacts
Erosive basal contacts
Sharp upper contacts
Well sorted
Similar grain size distribution as beach
Normally graded
Multiple normally graded pulses
Allochthonous marine diatoms
“Beach” diatoms

**Anecdotal Information**
American Indian legends
Figure 1.1 South Bay paleoseismic investigation location map and core stratigraphy.
The lower Eel River Valley was cored and cut-bank described extensively by Wenhao Li for his MS completed in 1992. Li used 48 gouge core descriptions and an untold width of cut bank exposures to test subsidence using foraminiferal zonation (Figure 1.4). Li concluded that 5 coseismic buried soils are recorded in stratigraphy along the lower Eel River Valley (Figure 1.5).

Subsequently Gary Carver used age control to refine an estimate of the age of burial for the most recently subsided soil. Tree rings from trees rooted in this soil were used for $^{14}$C age control (Figure 1.6). Carver and Plafker (see below, SSA abstract) conclude the Eel River Segment of the CsSz ruptured in the early 19th Century (Figure 1.7). The 1992 Petrolia earthquakes are used to further show evidence of CsSz segmentation (see below, SSA abstract).

**Wenhao Li (1992)**

**EVIDENCE FOR THE LATE HOLOCENE COSEISMIC SUBSIDENCE IN THE LOWER EEL RIVER VALLEY, HUMBOLDT COUNTY, NORTHERN CALIFORNIA: AN APPLICATION OF FORAMINIFERAL ZONATION TO INDICATE TECTONIC SUBMERGENCE**

**ABSTRACT**

At least 5 cycles of intertidal sedimentation punctuated by sudden episodes of submergence are recorded in the late Holocene stratigraphy from the lower part of the Eel River Valley, about 15 km south of Humboldt Bay in northern California. The sediments consist of estuarine muds that grade upward into peaty muds and peats. Peats contain salt marsh plant fossils, and at two locations buried weak soils contain rooted stumps of spruce trees. The estuarine muds contain Foraminiferid associations dominated by the lower intertidal *Miliammina fusca*. The change in Foraminiferid associations occurs across a stratigraphic distance of no more than 7-12 mm at the contact between the peats and overlying muds, reflecting sudden changes from upper intertidal to lower intertidal depositional environments. Conventional C14 age estimates for the fossil trees and marsh peats indicate ages for the sudden submergence episodes of about 300, 800, 1200, 1500, and 1900 ybp.

The study area is situated near the axis of the Eel River syncline, one of three large synclines in the fold and thrust belt of the Cascadia subduction zone which extends on shore of northern California. Similar bay-marsh sequences with similar age estimates have been reported for two other synclines in the area. The most likely cause for the sudden changes in sedimentation and Foraminiferid associations during the late Holocene are interpreted to be coseismic subsidence resulting from subduction earthquakes on the southern portion of the Cascadia subduction zone.
Figure 7. The field-work locations of hand augering cores, bank exposures, and vibracone sections in the study area, the lower Eel River valley, Humboldt County, northern California.

Figure 1.1 Core Location Map for Coring Campaign of Lower Eel River Valley (Figure 7, Li, 1992).
Figure 1.2 Composite core for Eel River stratigraphy from Li (Figure 13, Li, 1992). 14C age estimates are made from calibrated ages.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Vibracore Composite</th>
<th>Texture</th>
<th>Estimated Ages</th>
<th>Calibrated C14 dates (YBP)</th>
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<tr>
<td>0</td>
<td>Modern Peat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Tidal Mud</td>
<td></td>
<td></td>
<td>0-520</td>
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<td></td>
<td>First Peat &amp; Soil</td>
<td></td>
<td>300 YBP</td>
<td>0-630</td>
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<td></td>
<td>0-520</td>
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<td></td>
<td>0-530</td>
</tr>
<tr>
<td>200</td>
<td>Tidal Mud</td>
<td></td>
<td></td>
<td>620-1060</td>
</tr>
<tr>
<td></td>
<td>Tsunami Sand</td>
<td></td>
<td></td>
<td>540-970</td>
</tr>
<tr>
<td></td>
<td>Second Peat</td>
<td></td>
<td>800 YBP</td>
<td>670-1300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1009-1606</td>
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<tr>
<td></td>
<td>Third Peat</td>
<td></td>
<td>1200 YBP</td>
<td>960-1410</td>
</tr>
<tr>
<td></td>
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<td>1009-1606</td>
</tr>
<tr>
<td></td>
<td>Fourth Peat</td>
<td></td>
<td>1500 YBP</td>
<td>1170-1720</td>
</tr>
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<td></td>
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<td>1260-1710</td>
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<td></td>
<td></td>
<td>1340-1880</td>
</tr>
<tr>
<td>300</td>
<td>Tidal Mud</td>
<td></td>
<td></td>
<td>1590-2149</td>
</tr>
<tr>
<td></td>
<td>Fifth Peat &amp; Soil</td>
<td></td>
<td>1900 YBP</td>
<td>1590-2209</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>1614-2359</td>
</tr>
<tr>
<td>400</td>
<td>Tidal Mud</td>
<td></td>
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</tr>
</tbody>
</table>

Figure 13. Composite summary of the five repeated buried sequences in the lower Eel River valley. Five sequences were interpreted to result from coseismic subsidence and were dated by C14 on 18 analyses at about 300, 800, 1200, 1500 and 1900 ybp.
Plate interaction at the Mendocino triple junction is distributed across a broad region where wide, complex plate boundaries intersect. The San Andreas transform leg of the triple junction is made up of three principal fault zones separated by 30-50 km wide splinters of continental crust. The Mendocino transform leg includes the Mendocino fault and a broad zone of deformation that encompasses the southern part of the Gorda plate. The Cascadia megathrust and the 70 km wide Little Salmon and Mad River thrust systems in the upper plate accommodate plate convergence across the Cascadia subduction zone (CSZ). The intersection of the two wide transform boundaries with the 70 to 100 km wide southern end of the subduction zone results in changes in convergent vectors and rates and produces at least two kinematically-defined

Figure 1.3 Sketch of cores and bank exposure (Figure 8, Li, 1992). Trees used for age control by Carver (see Penrose abstract) and Carver and Plafker (see SSA abstract) may be in this figure.
subduction zone segments in the Mendocino triple junction region. The southern of these, the Petrolia segment, ruptured in 1992 producing the Ms 7.2 Petrolia earthquake. The northern Eel River segment has not ruptured historically, but high-precision 14-C ages of tree ring series from trees killed by saltwater immersion due to coseismic subsidence in the lower Eel River valley suggest the last rupture of this segment occurred in the early 1800s, about 100 years after the last rupture of the main CSZ to the north.

Penrose abstract

PALEOSEISMIC GEOLOGY OF THE SOUTHERN PART OF THE CASCADIA SUBDUCTION ZONE

Carver, Gary A., (Professor Emeritus) Department of Geology, Humboldt State University, Arcata, California, 95521; and Carver Geologic, Kodiak, Alaska, 99615, wooak@ptialaska.net.

During the last two decades geologic evidence of localized coseismic uplift, localized coseismic subsidence, surface fault rupture and tsunamis inundation has been identified at numerous coastal sites in northern California. This evidence, interpreted in the context of improved maps and models of the structure and tectonics at the southern end of the Cascadia subduction zone, provides a basis for characterization of repeated great earthquakes during the late Holocene.

The northern California coast differs from much of the rest of Cascadia in both its tectonic architecture and the type and structural context of the paleoseismic evidence. Between southern Oregon and the Mendocino triple junction the plate boundary is closer to shore and at a shallower depth beneath the coastline than it is along most of the Cascadia coast to the north. This places most of the northern California coastline west of the zero isobase in the region of general coseismic uplift. Additionally, a well developed fold and thrust belt, offshore along much of the northern part of the convergent margin, approaches the coast and extends onshore in northern California (Clarke and Carver, 1992). Two systems of large seaward vergent thrusts and associated folds, the Little Salmon and Mad River fault zones, make up the fold and thrust belt along the California part of the subduction zone. Late Quaternary slip on these thrusts and growth of the associated folds is reflected by progressive deformation of flights of raised marine terraces. Late Quaternary slip rates on these faults indicate they accommodate much of the plate convergence. Paleoseismic studies on several of these faults shows they have repeated late Holocene displacements.

Raised Holocene marine terraces and elevated shore platforms are present where anticlines intersect the coastline. Cover sediments on the raised terrace at Clam Beach contain buried soils within dune sequences and landslide ponded sediments that entomb fragile sedges in growth position. These sediments suggest the terrace was raised coseismically. Salt marsh stratigraphy with layers of peat, herbaceous salt marsh plants and trees buried by intertidal mud is localized in the cores of several large synclines. This stratigraphy, interpreted as recording coseismic subsidence (Jacoby et. al, 1995), is
absent at other places along the northern California coast. Radiocarbon ages for the raised Holocene terraces and the subsided marsh sequences are similar to ages for subsidence episodes along the subduction zone to the north (Atwater and Hemphill-Haley, 1997). High precision tree ring series radiocarbon ages from buried trees and AMS ages for entombed salt marsh plants at the north end of Humboldt Bay show the most recent subsidence event occurred within about a decade of AD 1700 (Nelson et. al., 1995).

Paleotsunami evidence is present in many wetlands along the northern California coast. The evidence includes sand sheets containing marine diatoms capped by woody debris layers and multiple fining upward sand sequences indicative of successive wave pulses typical of large run-up locally generated tsunamis. Radiocarbon ages for the paleotsunami sands from the south part of Humboldt Bay, Lagoon Creek, and Crescent City for the last 5 events are indistinguishable at the 2 sigma level from ages for Cascadia earthquakes on the Washington coast (Atwater and Hemphill-Haley, 1997). At several locations the tsunami sands are stratigraphically related to indicators of strong shaking including landslides and liquefaction and to sedimentologic, macro-floral and diatom evidence of coseismic subsidence.

At least two short subduction zone segments with slip histories different than the rest of Cascadia are present in the Mendocino triple junction region. These segments are kinematically defined by differences in convergence direction and rate resulting from the intersection of the subduction zone with the wide San Andreas and Mendocino fault - Gorda deformation zone transform systems (Tanioka et. al., 1995). In 1992 the southern segment ruptured and produced the Mw 7.2 Petrolia earthquake and up to 1.4 meters of coseismic uplift on a ~24 kilometer long section of coast south of Cape Mendocino. Tree ring series radiocarbon ages for subsided and buried trees in the Eel River delta on the northern segment indicate its last rupture occurred in the early 1800s. These segments constitute additional subduction earthquake sources at the south end of the Cascadia subduction zone.
Taken together, the paleoseismic evidence for Cascadia earthquakes in northern California suggests the subduction zone north of Humboldt Bay has a late Holocene seismic history that is similar to the rest of the Cascadia subduction zone in the Pacific Northwest. In northern California past great Cascadia earthquakes have included rupture of fold and thrust belt faults, particularly the Little Salmon fault, and growth of associated folds. This upper plate deformation accommodated much of the plate convergence. Coseismic elevation changes along the coast have been associated with the upper plate structures. Coseismic subsidence has been confined to syncline axis while uplift occurred where anticlines intersect the coast. Large tsunamis were produced during each late Holocene event. The timing of the last 5 northern California Cascadia earthquakes can not be differentiated on the basis of radiocarbon ages from those originating further north along the Washington coast, suggesting most of the subduction zone may be unsegmented during most seismic cycles. Two short subduction zone segments with different slip histories are recognized in the Mendocino triple junction region. The southern of these ruptured in 1992, and the northern segment probably last ruptured in the early 1800s.

I investigate evidence of coseismic subsidence in southern Humboldt Bay and the relation of this subsidence to Cascadia subduction zone earthquakes and to earthquakes on the Little Salmon fault, an active upper plate thrust fault that borders Humboldt Bay. Coseismic subsidence at Hookton Slough is correlated with paleo earthquakes at Swiss Hall, ca. 1 kilometer to the east. I identified five buried marsh soils over a 1-kilometer long transect along Hookton Slough, a tidal channel tributary in Humboldt Bay. Using the lateral extent of burial, the abrupt upper contacts to the soils, and the diatom biostratigraphy, soils subsided coseismically and those soil burials were accompanied by abrupt rises in relative sea level. I also infer that tsunami-transported sand, observed in the stratigraphy from Hookton Slough, was deposited directly on two soils at the time of subsidence. Buried soils at Hookton Slough are best explained by coseismic subsidence during Cascadia subduction zone earthquakes. Radiocarbon age estimates constrain timing of subsidence and allow me to estimate a recurrence interval of Cascadia subduction zone earthquakes in the Humboldt Bay region. A recurrence interval for these large earthquakes ranges from 650 to 720 years for the last 2,400 years. Three of the buried soils correlate to similar buried soils found at other sites around Humboldt Bay, and timing of subduction zone earthquakes at Hookton Slough overlaps with timing of earthquakes on the Little Salmon fault.

INTRODUCTION

The principal objective of this study is to identify buried tidal marsh soils in sediments near Hookton Slough and assess whether each soil was buried due to abrupt tectonic subsidence. Timing of the abrupt change is constrained with radiocarbon age determinations. I also investigate whether land level changes are concurrent with tsunamis in the Hookton Slough region. Finally, I attempt to correlate the Hookton Slough earthquake chronology to the regional earthquake history.

Evidence of abrupt land level changes caused by large magnitude earthquakes on the Cascadia subduction zone (Figure iii) can be identified from sediment cores extracted along the margin of Humboldt Bay. This coring study at Hookton Slough provides data to estimate the recurrence of abrupt land level changes and tsunami incursion within South Bay, which is in the southern part of Humboldt Bay (Figure ii), and compares these results with those results of previous studies (Carver and Burke, 1988; Vick, 1988; Clarke and Carver, 1992; Valentine, 1992; Carver and others, 1998; Witter and
others, 2002). I provide data on timing and extent of tsunami incursion into the South Bay. Additionally, I correlate Little Salmon fault scarp stratigraphy at the Swiss Hall site to similar stratigraphy further west on the bay margin at Hookton Slough site.

This study was conducted in estuarine deposits along the north flank of Table Bluff anticline, south of Hookton Slough. The Table Bluff anticline is the result of growth of an east-west striking north dipping blind reverse fault (Figure ii). Fault propagation folding is evident from onshore deep-penetration reverse fault (Carver, 1992). However, evidence of right-lateral strike-slip offsets of about 2-kilometers along a near vertical fault associated with the Table Bluff anticline is found in 1996 seismic profiles (Burger and others, 2002). The N70-90W Table Bluff anticline is composed of Plio-Pleistocene Wildcat Group sediments draped by a flight of marine terraces of Quaternary Hookton Formation consisting of fluvi to near-shore and beach sediments (Carver and Burke, 1992; Figure ii). Each abrasion platform is associated with a stable relative sea level high during an interglacial period. Since 332 ka anticlinal growth intersected with sea level highs and abrasion platforms were cut into the fold (Burger and others, 2002). Terraces mapped by Carver and Burke (1992) have younger terraces cut into the margins of Table Bluff; these younger terraces are directly south of Hookton Slough. Modern tidal flats may be overlying still younger abrasion platform(s). Hookton Slough, a tidal channel, cuts into these tidal flats and was probably formed from discharge of the largest tributary of southern Humboldt Bay, Salmon Creek.

Hookton Slough core sites are in a low-lying brackish marsh that mostly exists below mean higher high water (Figure 2.1). Levees constructed up to the late 1920s (Shapiro and others, 1980) now prevent tidal inundation to core sites. However, portions of the study area are perennially submerged because levees restrict drainage of ground and surface water. At times the study site becomes flooded with as much as two meters of standing water, and flooding contributes to the preservation of subsurface stratigraphy. In contrast, Valentine (1992) found that interpretation of Humboldt Bay stratigraphy in most areas immediately behind levees was impeded by oxidation in the upper 1 to 1.5 meters.

METHODS

Paleoseismic investigations provide data on earthquake history. Atwater (1987) first suggested evidence of coseismic deformation of late Holocene estuarine deposits along the coast of Washington. Atwater (1987); Clarke and Carver (1992); Clague and Bobrowsky (1994); Nelson and others (1996a, 1996b, 1998); Hemphill-Haley (1995); Atwater and Hemphill-Haley, (1997); Kelsey, and others (2002); and Witter and others (2003) interpret mid- to late-Holocene buried tidal marsh soils to be caused by vertical land-level changes related to Cascadia subduction zone earthquakes. Since buried soils are not exposed in cut banks in southern Humboldt Bay, research on buried soils requires coring in tidal marshes.
Figure 2.1 Hookton Slough core location map. Blue circles mark locations of gouge cores. Yellow circles mark locations of vibra cores. West, Center, and East transects are separated by historic tidal channels in green. 1912 high tide line in blue shows that all core locations were tidally inundated before the levees were constructed (Coast and Geodetic Survey, chart 18622, 1912). Tide gates permit partial tidal influence to study area. Imagery is a USGS panchromatic Digital Orthophoto Quarter Quadrangle (DOQQ), Fields Landing, 1989, with one meter pixels.
Subsurface stratigraphy was determined with a core transect located parallel to Hookton Road (Figure 2.1). This allowed me to contour the pre-historic margin of southern Humboldt Bay just east of the Hookton Road boat ramp.

Closely spaced borings are required to correlate stratigraphy among cores. Fifty-three, 3-centimeter diameter gouge cores were hand driven to sample subsurface stratigraphy along the one kilometer transect: West, Center, and East Sections (Figure 2.1). The cores were driven down to 6 meters depth or until resistance by coarse sediment (pebbles up to 3-centimeter diameter) prevented further penetration. The core transect is sub-parallel to the break in slope, along the historic high tide line. Three main sub-transects, West, Center, and East sections, are separated by historic channels (blue lines; Figure 2.1). There are three slope-perpendicular profiles, one in each sub-transect, labeled Profiles A-A', B-B', & C-C' (Figure 2.1). Core stratigraphy of slope-perpendicular transects shows that the buried deposits lap onto upland stratigraphy to the south.

Stratigraphy within each core was recorded by color, texture, structure, roots, and nature of contact. Distinct horizons were correlated among cores based on lithostratigraphy and depth.

In addition to gouge cores, vibra cores (7.5-centimeter diameter aluminum tubes) were taken at sites where gouge cores had the most complete stratigraphic section. Vibra cores are driven into the ground by vibrating the tubing with a gasoline engine and are removed from the ground with a ratcheting winch. In contrast to gouge cores, vibra cores provide larger quantities of sample for paleoenvironmental and radiocarbon analysis. Also, variation in the nature of the contacts between strata is clearer with the larger cross sectional area of the vibra cores.

Fossil diatoms sampled from specific strata in vibra cores are used to infer changes in paleoenvironment relative to mean tidal level. Paleoenvironmental interpretation is based on the observation that Humboldt Bay organisms live in tidal range-restricted habitats based on salinity (Li, 1992; Manhart, 1992; Carver and others, 1998). Hemphill-Haley (1995) developed techniques to estimate paleoenvironment based on diatom assemblages in Willapa Bay, Washington using the Brackish Intertidal Diatom Index (BIDI). The BIDI is a ratio of the counts of groups of diatoms based on their modern tidal range and provides a qualitative estimate of paleoenvironment. BIDI values range from zero, inferring a sub-tidal environment, to one, inferring a more freshwater, high-marsh environment.

Diatom samples were chosen immediately above and below the top of the buried soil to test the abruptness of environmental change. Samples were also chosen several centimeters above and below the contact to test that the samples represent the paleoenvironment of the sampled unit. A sample is chosen more distant up section from the contact to test the permanence of the environmental change.

If buried soils are to be considered evidence for coseismic subsidence, there are five criteria that could be satisfied (Nelson, 1996b). They include (1) suddenness of
submergence, (2) submergence greater than or equal to 0.5 meters, (3) lateral extent of submergence over hundreds of meters, (4) coincidence of submergence with tsunami sands, and (5) synchronous submergence of correlative buried soils. In addition, Hemphill-Haley (1995) suggests three additional criteria: a significant change in diatom assemblage across stratigraphic contact inferring a sudden change in land elevation, submergence indicated by the persistence of environmental change, and the presence of sand flat diatom species in the sand capping the mud. In this study not all five criteria were satisfied in order to demonstrate coseismic subsidence.

Age control for deposits is constrained using accelerator mass spectrometry $^{14}$C age estimates (Jacoby and others, 1995; Nelson and others, 1996b; Atwater and Hemphill-Haley, 1997). Only identifiable plant material was used for age control. While detrital material provides a maximum limiting age, in situ material provides a minimum limiting age. Samples that likely persist through time (large chunks of wood, charcoal) were not chosen because they are more likely to be reworked, thus overestimating the age of the deposit. Radiocarbon samples were first wet-sieved with a #100 (0.5 millimeter) screen, then identified, and then dried and sent to Geochron Laboratories for accelerator mass spectrometry $^{14}$C analyses. Finally, radiocarbon age determinations were converted from lab reported radiocarbon years to calendar years to constrain the timing of inferred earthquakes and tsunamis.

RESULTS

The Hookton Slough cores show evidence of soils recurrently buried suddenly by mud to muddy peat. Sandy deposits abruptly overlie three buried soils. Abrupt and persistent paleoenvironment change as inferred from diatom analysis accompanies the abrupt and persistent lithostratigraphic change. Accelerator mass spectrometry $^{14}$C age estimates constrain the timing of these changes.

Lithostratigraphy

Hookton Slough cores show cycles of peat that are commonly first overlain by sandy deposits and then overlain by muds. Correlation of units among closely spaced cores is based on stratigraphy (Figure 2.2).

Five buried muddy-peat to peat horizons are found (buried soils 1-5). Soil 1 is the most recent buried soil and soil 5 is the oldest buried soil. The soils are abruptly buried by either muds (soils 5 and 2) or by sands (soils 1, 3, and 4). The soils contain up to 100% fibrous peat.

The mud found between the buried soils has an abrupt (< 2 cm) lower contact (Figure 2.3) and a gradual (5 to 15 cm) upper contact. The abrupt lower contact indicates a rapid stratigraphic change and the gradual upper contact indicates a slower stratigraphic change. The mud consists of silty clay to silt loam. Thickness of mud between soils 3 and 4 is greater and more variable than the thickness of the mud
Vibra Core Mosaic

Figure 2.2 Hookton Slough vibra core stratigraphy for nine vibra cores. Triangles mark location of age control samples for vibra cores only. BIDI values indicate fossil diatom sample locations. Photo mosaic for each column is composed of six to fifteen overlapped photos. Peats are labeled with encircled numbers. Tsunami deposits are shown with encircled “t.” Elevation is relative to MLLW for NOAA tidal benchmark (PID K1087).
between soils 2 (or 1) and 3. Rhyzoconcretions (stiffer mud surrounding root pores, commonly reddish brown in color, possibly due to iron oxidation) were found between soils 2 and 3. Underlying rhyzoconcretions were millimeter scale black laminations.

The sand overlying soils 3 and 4 commonly consists of multiple normally graded beds of sand to sandy loam. The sand’s lower contact is abrupt, often with a wavy 1- to 4-centimeter relief. Commonly incorporated within the sand are 0.5- to 3-centimeter diameter rip-up clasts consisting of pieces of mud and pieces of fibrous peat (possibly from the underlying soil; Figure 2.3).

Coarse gravelly sand to sandy loam defines the depth of core refusal, which ranges from 1.5 to 6.1 meters depth (Figure 2.3). These sediments are blue gray at the top and change downward to orange tan. I interpret these deposits to be colluvium from the Pleistocene Hookton Formation, found in outcrop directly upslope to the south of the coring transect. In cores proximal to the upland, soil 4 is commonly developed in the top of this unit. Soil 5, found deeper in a core further north (away from the upland) is developed in mud also overlying this unit.

Biostratigraphy

Based on plants (Triglochin) and diatom assemblages, soils found at Hookton Slough were likely developed in high marsh to upland environments and muds were deposited in low marsh environments (Figure 2.4). Environmental change inferred from fossil diatoms in cores 5A and 49 (analysis by Eileen Hemphill-Haley) reflects a high marsh to upland paleoenvironment abruptly changing to a tidal flat paleoenvironment for burial of soil four and a low marsh paleoenvironment to tidal flat paleoenvironment for burial of soil three (Figure 2.4). The abrupt change in inferred environment correlates with abrupt lithostratigraphic change. A freshwater paleoenvironment of the coarse gravelly sand to sandy loam below the buried soils is based on diatoms and the presence of phytoliths.

Radiocarbon Age Determinations

Hookton Slough buried soils 1, 3, and 4 contained materials suitable for radiocarbon age determinations (Figure 2.5). Age control is poor to non-existent for soils 1 and 2. A radiocarbon age for soil 1, using a sample of more than forty seeds, is 100 ± 40 14C yr BP (BP = before A.D. 1950). This radiocarbon age (Figure 2.5) is consistent with the inference that the soil subsided during the A.D. 1700 Cascadia subduction zone earthquake; but the calibrated age range (A.D. 1950 to A.D. 1677) is broad. Soil 2 did not contain material suitable for age determination. The ten radiocarbon age determinations for soil 3 include three which are based on seeds, one based on a twig with bark, and six based on triglochin leaf bases (Figure 2.5). The seven soil 4 radiocarbon
DISCUSSION

Subsidence Mechanism

Criteria used to infer coseismic subsidence of the five soils identified from cores in Hookton Slough include: 1) suddenness of change in depositional environment, 2) amount of subsidence, 3) lateral extent, 4) presence of sand capping peat, and 5) ages include two of which are from seeds, one from a conifer leaf, one from a twig with bark, two from vascular plant leaves, and one based on an in situ triglochin rhizome (Figure 2.5). The two soil 5 age determinations are from detrital material from the same horizon in the same core and provide the same ages (Figure 2.5).

Figure 2.3 Close-up of view of strata in vibra-core 26 interval 147-174 centimeters depth below the ground surface. Fibrous peat is overlain by coarse sand to pebble deposit with up to 1-centimeter diameter fibrous peat and silt loam rip up clasts along an abrupt wavy contact. Sand is gradually overlain by silt loam.
Vibra Core 5a

Brackish Intertidal Diatom Index (BIDI)
BIDI is a statistical ratio to relating diatom assemblages to inferred paleoenvironment (Hemphill-Haley, 1995, 1997).

\[
\text{BIDI} = \frac{H + B + L/2}{H + B + L + T}
\]

Figure 2.4 Diatom biostratigraphy in core 5a using the Brackish Intertidal Diatom Index (BIDI), developed by Hemphill-Haley (1995). In conjunction with disconformities above peats three and four, an abrupt change in inferred paleoenvironment occurs. Note that environmental change is persistent.
Figure 2.5 Radiocarbon results for Hookton Slough are displayed with probability density functions as determined with OxCal calibration software (Bronk Ramsey, 1995, 2001). X-axis is time as measured backwards from 1950, Y-axis is sample probability function of each sample. Sample number syntax for ‘48 215.5 1990±40BP’ is (48) core number; (215.5) depth to top of sample interval; (1990) laboratory reported age; (±40) laboratory error; (BP) is before present, where present is A.D. 1950. Data are sorted by soil with color. Soil 1, yellow; Soil 3, blue; Soil 4, green; and Soil 5, purple. Distance to contact is the minimum and maximum distance between the sample intervals’ upper and lower contact and the contact between the upper or lower unit. An ‘up’ arrow depicts a sample from below a contact. A ‘down’ arrow depicts a sample from above a contact. Atmospheric data from Stuiver and others (1998a, 1998b); Calibration software: OxCal v3.5 (Bronk Ramsey 1995, 2001); and Calib (Stuiver and Reimer, 1986, 1993).
synchronicity of buried soils (Nelson, 1996b; Hemphill-Haley, 1995). These criteria are satisfied robustly for three of the five soils (Table 2.1).

Possible alternative explanations for all soil burials include cut-and-fill by tidal streams, sediment deposition by storms or floods, fluctuations in sea level, or intermittent closure of the mouth to Humboldt Bay. None of these alternative explanations is supported by field data.

For example, extensive lateral continuity of the buried soils’ upper contacts eliminates tidal stream cut-and-fill as a mechanism for stratigraphy found at Hookton Slough. Cut-and-fill by tidal streams would produce stratal contacts with a relief equal to the depth of stream scour. The upper contact of buried soil 3 has a low relief (0.5 meter). The thickness of soil 4 is also consistent throughout the relief of the upper contact. This suggests that the disconformity is unlikely to have been caused by localized erosion across the contact due to tidal streams.

It is unlikely that storms or floods were the cause of soil burial at Hookton Slough because sediment deposition during storms or floods would increase the ground elevation. To the contrary, fossil diatoms observed in stratigraphy at Hookton Slough show a lowering in elevation across the peat-mud contact. However, due to a lack of paleontological evidence, there is greater uncertainty about whether soil 1 or soil 2 were buried by storm or flood deposits.

Fossil diatom changes are consistent with an abrupt long-lasting rise in relative sea level and not with sea level fluctuations occurring over periods of months to decades for burial of soils three and four. Furthermore, upper contacts of the buried soils at Hookton Slough are abrupt, and therefore are unlikely to be a response to gradual sea-level fluctuation.

Bay-mouth barrier formation and breaching may explain mud overlying soils, but all maps since 1852 show the mouth in the current location. In the last 150 years the mouth has always stayed open (up to twenty meters depth in 1894. United States Coast

<table>
<thead>
<tr>
<th>Buried Soil</th>
<th>Number of cores that sampled buried soil *</th>
<th>Minimum lateral extent of buried soil * (M)</th>
<th>Depth range of buried soil (MLLW, cm) †</th>
<th>Number of cores with overlying sandy deposit *</th>
<th>Maximum thickness (cm) of sandy deposit</th>
<th>Maximum number of beds in sandy deposit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>44</td>
<td>940 m</td>
<td>111 to 41</td>
<td>1</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>900 m</td>
<td>75 to 22</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>29</td>
<td>1,000 m</td>
<td>-28 to -153</td>
<td>4</td>
<td>24</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>920 m</td>
<td>-121 to -353</td>
<td>9</td>
<td>45</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1 m</td>
<td>-380</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* see Figure 10
† Mean Lower Low Water (MLLW)

Table 2.1 Lateral Extent and stratigraphic characteristics for the buried soils at Hookton Slough, Humboldt Bay.
and Geodetic Survey). Even though this amount of time is short when compared to the stratigraphic record found at Hookton Slough, this evidence shows that in historic times the mouth is in equilibrium with the relations between freshwater discharge into the bay, tidal exchange of sea-water, and sediment budget for the littoral cell of Humboldt Bay.

Fluvial discharge from tributaries into Humboldt Bay is probably sufficient to maintain the bay mouth. In Willapa Bay, Washington, Atwater and Hemphill-Haley (1997) suggest there may be too much freshwater discharge into the bay to allow deposition of a sand barrier across the bay mouth. Elk River, Freshwater Creek, Jacoby Creek, Jolly Giant Creek, Salmon Creek, and other tributaries into Humboldt Bay generate sufficient discharge to maintain the mouth. If the bay mouth were closed for a sufficient time, freshwater diatoms would be found in the mud capping the soils, whereas Hookton Slough fossil diatoms are consistent with a continuous tidal environment for the last 2,400 years.

In summary, abrupt and persistent lithostratigraphic and biostratigraphic changes coincide in sufficient frequency and over a sufficiently broad area (at least 48,000 m²) to verify the inference that several tidal marsh soils at Hookton Slough were buried by coseismic subsidence accompanying Cascadia subduction zone earthquakes. I conclude that coseismic subsidence occurred five times in the Hookton Slough region in the last 3,700 years.

Subsidence Magnitude

Estimates of subsidence magnitude may be made using two methods: the paleoelevation estimate and the pre-burial ground surface relief estimate. Paleoenvironment based on fossil diatoms is used to estimate paleoelevation range (Kelsey and others, 2002; Witter and others, 2003; Table 2.2; Figure 2.6). Paleoenvironment is based on elevation relations between modern vascular plants and modern diatom zonation in southern Oregon (Nelson and Kashima, 1993). Changes of paleoelevation are determined by subtracting paleoelevation ranges of the buried soil from the overlying mud (Table 2.2; Figure 2.6-A). Minimum and maximum paleoelevation estimates of submergence for soil 4 are 0.9 and 3.1 meters, respectively. Minimum and maximum paleoelevation estimates of submergence for soil 3 are 0.0 and 1.6 meters, respectively. Because the upland and mudflat elevation ranges are limited to 1 meter by truncating the unbounded upper and lower ends respectively (Figure 2.6), this method does not measure maximum submergence greater than 3.1 meters. Therefore, the maximum submergence estimate can be larger and is thus a lower limiting maximum.

For estimates using relief measurements, minimum submergence is larger than the paleoelevation method (Table 2.2). Assuming the relief of buried soil 4’s upper contact represents pre-existing topography, all of soil 4 was in an upland setting, and mud overlying buried soil 4 was deposited in a tidal flat setting (Figure 2.6). In order to test that all of soil 4 was in an upland setting, diatom paleoenvironment estimates must be made...
in cores that have soil 4 in the lowest and the highest position. Pre-subsidence elevation of soil 4 is constrained by paleoelevation estimate for sediment sampled from core 5A (Figure 2.6-B, a). Post subsidence elevation control is based on the highest position for soil 4 being at the highest elevation in the mudflat ecological range (Figure 2.6-B, c). Minimum submergence estimates are made by subtracting the lowest possible elevation of the topographically highest position of soil 4 in core 5A (pre-subsidence elevation minimum = 3.2-meters MLLW; Figure 2.6-B, b) from the highest possible elevation of the same highest topographic position of soil 4 in core 5A (post-subsidence elevation maximum = 0.3-meters MLLW; Figure 2.6-B, c). Modern tidal range is almost as large as the relief of soil 4. Only soil 4 upper contacts are sufficiently large with respect to tidal range to reliably use the relief method for a submergence estimate. The paleoelevation minimum subsidence estimate cannot measure submergence larger than 0.9 meters. Given the uncertainty in paleoelevation estimates for the range of elevations of soil 4, topographically above soil 4 in core 5A, the relief derived minimum submergence estimate for soil 4 is 2.9 meters.

Maximum submergence cannot be completely measured with either method, because upper bounds of upland environments and lower bounds of mudflat environments cannot be constrained. Maximum submergence estimate methods need to be improved to better estimate subsidence maxima. Because the paleoelevation method cannot measure minimum submergence greater than 0.9 meters, the soil relief method is necessary in future studies to make better estimates of submergence in cases where subsidence may be greater than 0.9 meters.

**Coarse Sediment Deposition**

There are several stratigraphic and paleontologic attributes of the Hookton Slough sandy sediment (“sand”) that lead me to interpret that it is of tsunamigenic origin. These include: 1) the association of sand with an abrupt relative sea level rise, 2) an abrupt erosive lower contact of the sand overlying the buried soils, 3) rip-up clasts

table 2.2 Paleoelevation and submergence estimates for buried soils at Hookton Slough.

<table>
<thead>
<tr>
<th>Buried soil</th>
<th>BIDI *</th>
<th>Elevation paleo MTL (m) #</th>
<th>Median submergence</th>
<th>Minimum / maximum submergence</th>
<th>Relief minimum subsidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil 3</td>
<td>0.56</td>
<td>0 to 0.9</td>
<td>0.65 m</td>
<td>0 m to 1.6 m</td>
<td>ND †</td>
</tr>
<tr>
<td></td>
<td>0.01</td>
<td>-0.7 to 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil 4</td>
<td>1</td>
<td>1.4 to 4.9</td>
<td>2.1 m</td>
<td>0.9 m to 3.1 m</td>
<td>2.9 m</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td>-0.7 to 0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Brackish Intertidal Diatom Index
# Mean Tide Level
† cannot be determined with this method
of mud and peat are within the sand, 4) the presence of unbroken sand flat diatom species, and 5) the multiple upward fining beds in the sand layers. I interpret that a sand-laden tsunami inundated Hookton Slough following at least two coseismic subsidence events. Rip-up clasts and sand intrusions into the underlying soil imply the tsunami had high flow velocities sufficient to erode the buried soil substrate. Multiple fining-upward sandy beds imply that the tsunami for each earthquake consisted of multiple waves. The coincidence of the tsunami deposits and the soil burial, taken together, support the conclusion that Cascadia subduction zone earthquakes caused the subsidence at Hookton Slough.

In addition to tsunami deposits associated with buried soils 3 and 4 at Hookton Slough, Carver and others (1998) identified tsunami deposits in southwestern Humboldt Bay, six kilometers west of the Hookton Slough site (Figs. ii). These deposits thin landward to a few centimeters, and Carver and others (1998) concluded that the tsunami that mobilized these sandy deposits overtopped the sand spit due west of their core sites. It is unlikely that the same tsunami waves carried sediment eastward to Hookton Slough because the Hookton Slough tsunami deposits are thicker, up to 45 centimeters. An alternative explanation is that the same tsunami locally overtopped the South Spit, depositing thin sand sheets at the southwest corner of the bay, and simultaneously flowed through the bay mouth and up South Bay tidal channels, depositing thicker tsunami deposits at Hookton Slough. Tsunamis that concentrate in tidal channels are well documented near Port Alberni, British Columbia (Clague and others, 2000; Figure iii).

**Ages of Coseismic Subsidence Events**

Hookton Slough stratigraphy records at least five coseismic events within the last 3,700 years. Radiocarbon age estimates are made on four of the inferred events (Figure 2.7).

In summary (Table 2.3), I infer five subduction zone earthquakes in the last ca. 3,500 years in southern Humboldt Bay. The most recent was the A.D. 1700 earthquake and the other three age constrained buried soils (3, 4, and 5) record earthquakes in the age windows of 1,350 to 2,150 yrs BP, 2,200 to 2,400 yrs BP, and 3,450 to 3,650 yrs BP respectively (Table 2.3).

**Recurrence Interval for Subduction Zone Earthquakes**

A recurrence interval estimate for subduction zone earthquakes causing coseismic subsidence near Hookton Slough is 650 to 720 years. This estimate assumes buried soils 1, 2, 3, and 4 each record a subduction zone earthquake. Three interseismic intervals that span these four soils have a cumulative age span of 1,950 to 2,150 years assuming soil 1 subsided in 250 years BP and soil 4 subsided 2,200 to 2,400 years BP. Three intervals in a 2,200 to 2,400 year period yield a 650 to 720 year recurrence interval.
Subsidence Estimate Figure

Figure 2.6 Subsidence magnitude estimates are made using paleoelevation and topographic relief methods. A. Changes of paleoelevation are determined by subtracting paleoelevation ranges of the buried soil from the overlying mud. B. Minimum submergence estimates are made by subtracting the lowest possible elevation of the topographically highest position of soil 4 in core 5A (post-subsidence elevation minimum = 3.2-meters MLLW; Fig. 12-B, b) from the highest possible elevation of the same highest topographic position of soil 4 in core 5A (post-subsidence elevation maximum = 0.3-meters MLLW; Fig. 12-B, c). Pre-subsidence elevation of soil 4 is constrained by paleoelevation estimate for sediment sampled from core 5A (Fig. 12-B, a). Post subsidence elevation control is based on the position of the highest position for soil 4 being at the highest elevation in the mudflat ecological range (Fig. 12-B, c). C. Diatom zonation is based on modern diatom ecology from coastal marshes in Oregon. The upper limit of the upland elevation range is truncated so that the range is 1 meter (Kelsey and others, 2002, Witter and others, 2003). Likewise, the mudflat elevation range is truncated on the lower end so that the range is 1 meter.
Figure 2.7 Probability Density Function plots of sequence analysis procedure using Bronk-Ramsey (1995, 2001). Lab reported age estimates are combined before calibration resulting in averaged calibration ages. Interpreted age ranges for each buried soil are delineated by rectangles. Due to potential problems with soil 3 sample material, soil 3 age is determined with the span of individual calibrated ages. Soils 4 and 5 ages are interpreted from calibrated average ages. Sample nomenclature and axis values are the same as for figure 9.
In comparison to other recurrence interval estimates for Cascadia subduction zone earthquakes from sites that have more than 2,500 years of earthquake record, Hookton Slough recurrence interval estimates are large. Using stratigraphy from sites along much of the entire Humboldt Bay margin, Valentine (1992) estimates a recurrence interval of 220 to 420 years over the last 4,300 years. Kelsey and others (2002) compute a 480 to 585 year recurrence interval at Sixes River estuary, Oregon, using 5,600 years of record, Witter and others (2003) compute a 570 to 590 year recurrence interval at the Coquille River estuary using 6,720 years of record, and Atwater and Hemphill-Haley (1997) compute a 500 to 540 year recurrence interval at Willapa Bay, Washington estuary over the last 3,500 years.

The Hookton Slough recurrence interval estimate of 650 to 720 years may be large compared to sites to the north for several reasons. Hookton Slough stratigraphy may be missing an earthquake in the 250 to 2,000 year period. This ghost earthquake may not be recorded because it did not cause subsidence to be preserved in the strata.
Alternatively, earthquakes on the Cascadia subduction zone could have occurred more frequently in the 1,000 to 2,000 year period prior to 2,400 years BP, a time period not recorded at Hookton Slough but recorded in the strata in southern Oregon and southern Washington. Another possibility is that an earthquake may be preserved in the strata but I did not recognize it.

A small sample size may be a limiting factor as well. Perhaps four to eight earthquakes is insufficient to capture the full range of variance for the recurrence of Cascadia subduction zone earthquakes. Future research is necessary to confirm or refute the presence of a ghost earthquake.

Correlation of Hookton Slough Earthquake Record to other Humboldt Bay Paleoseismic Sites and Tectonic Role of Little Salmon Fault

Using radiocarbon ages and stratigraphic relations, I correlate earthquake records at Hookton Slough to other Humboldt Bay paleoseismic sites at Salmon Creek valley (Carver and Burke, 1988; Clarke and Carver, 1992), Swiss Hall (Witter and others, 2002), and Mad River Slough (Vick, 1988; Jacoby and others, 1995)(Figure 2.8, Appendix 2.1). I did not use Valentine (1992) radiocarbon ages for correlation in Humboldt Bay because all 14C ages are from bulk peat samples and ages are not systematically older with depth in cores for southern Humboldt Bay (Appendix 2.1).

I consider radiocarbon ages for buried soils at Mad River slough (Vick 1988; Jacoby and others, 1995; Appendix 2.1). Up to four subsidence events are found by Vick (1988). One Mad River Slough earthquake (Mad River Slough event Y, Figure 2.8) correlates with an earthquake at Hookton Slough (Hookton Slough event 1, Figure 2.8). There are diatom paleoecologic data for the two upper most Mad River slough buried soils (Chad Pritchard, personal communication, 2004) and there are Foraminiferid paleoecologic data for the A.D. 1700 Mad River slough buried soil (Manhart, 1992). Due to lack of paleoecologic data, other buried soils at Mad River slough may not have been caused by an earthquake (Chad Pritchard, personal communication, 2004).

Inferred earthquakes near Swiss Hall (located two to three kilometers east of Hookton Slough) are correlated with inferred coseismic subsidence events at Hookton Slough (Figure 2.8). At the Swiss Hall site there is evidence for three, and possibly four earthquakes in sediment cores and trenches that crossed the western trace of the Little Salmon fault at the bay margin (events 1, 2, 3, and 4, Figure 2.8). Based on stratigraphic relations and fossil diatom evidence, Witter and others (2002) conclude that the study site coseismically subsided three times, over an estimated area of at least 5,500 m² (events 2, 3, and 4, Figure 2.8). Witter and others (2002) also conclude that the study site also folded the buried soils during at least one event on the Little Salmon fault (event 1, Figure 2.8). Within radiocarbon error, three buried soils (Hookton Slough events 2, 3, and 4, Figure 2.8) at Hookton Slough appear to correlate with three buried soils at Swiss Hall (Swiss Hall events 2, 3, and 4, Figure 2.8). Within radiocarbon error Hookton Slough buried
soil 1 correlates to the Swiss Hall folding event 1 (Figure 2.8). At Hookton Slough three of the correlative buried soils (soils 1, 3, and 4) are capped by sand sheets that include multiple graded beds and mud or peat or peaty mud rip-up clasts.

Salmon Creek valley fault trench studies conclude three earthquakes occurred in the last 2,000 years (Figure 2.8, Appendix 2.1). Within large radiocarbon age determination error, three earthquakes at Hookton Slough (Hookton Slough events 1, 2, and 3, Figure 2.8) correlate with three earthquakes at Salmon Creek Valley (Salmon Creek valley events 1, 2, and 3, Figure 2.8). Salmon Creek valley fault relations record Little Salmon fault history. Hookton Slough strata record Cascadia subduction zone earthquake induced subsidence. If these three earthquakes are correlative, then both Little Salmon fault and Cascadia subduction zone earthquakes coincide. If Hookton Slough is sensitive to both Cascadia subduction zone and Little Salmon fault earthquakes, and Little Salmon fault earthquakes are independent and chronologically distinct, then we would expect more earthquakes in the stratigraphic record at
Hookton Slough (which we don’t). Therefore, either 1) Cascadia subduction zone and Little Salmon fault earthquakes are coincident and Hookton Slough is sensitive to both earthquakes’ deformation, 2) Cascadia subduction zone and Little Salmon fault earthquakes are not coincident and Hookton Slough is not sensitive to Little Salmon fault earthquake deformation, but sensitive only to Cascadia subduction zone deformation, or 3) Cascadia subduction zone and Little Salmon fault earthquakes are coincident and Hookton Slough is not sensitive to Little Salmon fault earthquake deformation, but sensitive to Cascadia subduction zone deformation. Swiss Hall is probably sensitive to both Cascadia subduction zone earthquakes and Little Salmon fault earthquakes. Witter and others (2002) conclude that subsidence at Swiss Hall may be due to either the Cascadia subduction zone or the Little Salmon fault. However, for the earthquake that buried soils ca. 540 – 1,230 years BP, subsidence occurred in both the footwall and the hanging wall (Witter and others, 2002). Therefore, the Cascadia subduction zone is probably responsible for the subsidence during this earthquake.

Together the Hookton Slough and Swiss Hall studies demonstrate that, at least for some earthquakes, coseismic subsidence caused by earthquakes on the Cascadia subduction zone extends thousands of meters in the southern Humboldt Bay region and was coincident with generation of large tsunamis and may be coincident with earthquakes on the Little Salmon fault.

CONCLUSION

Southern Humboldt Bay has experienced at least four and possibly five Cascadia subduction zone earthquakes that caused subsidence and burial of tidal marsh soils in the past 3,700 years. Tsunami incursion in southern Humboldt Bay coincided with at least two earthquakes in the last 2,450 years. Preservation of tsunami deposits is highly localized.

Earthquakes at Hookton Slough occurred between 3,650 and 3,450, between 2,400 and 2,200, between 2,150 and 1,350, probably between 1,350 and 250, and finally around 250 years before A.D. 1950.

Four of these soils are correlated with earthquakes at the Swiss Hall site and they may correlate to the last three earthquakes at the Salmon Creek Valley trench site. A recurrence interval estimate for subduction zone earthquakes causing coseismic subsidence near Hookton Slough is 650 to 720 years.

Coincidence of tsunami deposits with abrupt subsidence provides evidence that Cascadia subduction zone earthquakes caused the subsidence observed at Hookton Slough and Swiss Hall. Within radiocarbon age determination error, upper-plate Little Salmon fault earthquakes are coincident with Cascadia subduction zone earthquakes and thus the Little Salmon fault may not be a source of coseismic subsidence independent of the subduction zone.
Arcata Bay contains the most extensively studied marsh stratigraphy in the Humboldt Bay region. Between 1988 and 2004 at least 7 major studies have been conducted there, most as M.S. theses at Humboldt State University. In the Mad River Slough area Vick (1988), Manhart (1992), Clark and Carver (1992), and Jacoby (1995) are the best sources for data. Vick conducted the initial coring while Manhart investigated the foraminifera biostratigraphy. These M.S. theses were followed in 1992 by Clark and Carver who refined the stratigraphy and 1995 by Jacoby who used dendrochonology to estimate the occurrence of the most recent subsidence event at 1700AD. The marsh stratigraphy of the eastern portion of Arcata Bay was catalogued by Dave Valentine in 1992 and the western portion by Leroy and Patton (Figure 3-1).

Pritchard (2004)
LATE HOLOCENE RELATIVE SEA-LEVEL CHANGES, ARCATA BAY, CALIFORNIA: EVALUATION OF FRESHWATER SYNCLINE MOVEMENT USING RECENT COSEISMICALLY BURIED SOILS

In 2004 Chad Pritchard re-occupied sites at Mad River Slough, Jacoby Creek, Eureka Slough, and Daby Island and cored a new location at the Arcata Salt Marsh. With this new information, and the previous studies, Pritchard summarized and compared the ages of the buried soil horizons from the Arcata Bay area. In his thesis he refers to the soils as; Sa, Sb, Sc, and Sd with soil Sa being the youngest most recently submerged soil.

“Soil Sa (youngest buried soil)

Soil Sa is laterally extensive among the five sites, spanning the area of Arcata Bay (34km²). Based on diatom biostratigraphic data from the Arcata Marsh site, Soil Sa subsided abruptly, changing from low marsh to tidal flat environment. Environmental change was long lasting, as is evident by the greater that 10 cm of tidal mud accreted above soil Sa.

The youngest buried soil has been dated by Valentine (1992) at Jacoby Creek, Daby Island, and Eureka Slough; at Mad River Slough by Vick (1988), Valentine (1992), Clarke and Carver (1992), Carver et al. (1992); and at the Arcata Salt marsh during this study. Furthermore, Jacoby et al. (1995) showed that trees and herbs at Mad River Slough were killed by an earthquake about 300 years ago. All ages are consistent with the inference soil Sa subsided during the January 26, 1700 A.D. earthquake that affected the entire Cascadia subduction zone....

Soil Sb and Sc (second and third buried soils)

Soils Sb and Sc are only present at the Mad River Slough site. Based on radiocarbon samples from this study and Vick (1988), soils Sb and Sc are indistinguishable by radiocarbon age; both ages are about 1200 cal yr BP.
Lithostratigraphically, an inorganic mud does not separate the second and third youngest buried soils at Mad River Slough. The intervening sediment, 35 to 80 cm thick, is a peaty mud with 30 to 15% organic content. The absence of massive, <15% organic mud may indicate another form of marsh burial, or a smaller amount of subsidence.

Biostratigraphically, the second youngest soil, Sb, at Mad River Slough was abruptly buried by tidal flat sediment. In contrast, the third youngest soil, Sc, at Mad River Slough was gradually buried by sediment deposited in an environment that had both tidal mud sedimentation and peat accumulation, reflected lithostratigraphically by the presence of peaty mud overlying this buried soil.

Soil Sb most likely represents a southern CSZ earthquake because it was abruptly subsided such that tidal mud buried a low marsh. However, Soil Sb is not preserved at the other four Arcata Bay sites. Soil Sb may only be preserved at Mad River Slough due to the lack of constant fluvial input and increased relative distance from the bay mouth.

Soil Sc, only recovered at Mad River Slough, has weak evidence for coseismic subsidence because it is not laterally extensive in Arcata Bay and more importantly, it does not have biostratigraphic evidence of rapid submergence from low marsh to tidal flat environment. Although, soil Sc may have been coseismically subsided other burial mechanisms are possible.....Other Studies have found two closely spaced CSZ earthquakes around 1200 yr BP, giving credence to the hypothesis of a Coseismic subsidence origin for the second and third youngest buried soils (Li, 1992; Nelson et al, 1996, Atwater and Hemphill-Haley, 1997; Abramson, 1998; Garrison-Laney, 1988). I infer that soil Sc questionably represents an earthquake, designated as earthquake “c”.

Soil Sd (fourth youngest buried soil)
Soil Sd is present at the Jacoby Creek and Arcata salt marsh sites, has consistent radiocarbon ages of 1630+/-40 (Arcata salt marsh, this study), 1610+/-40 (Jacoby Creek, this study), and 1660+/-40 (Jacoby Creek, Valentine (1992)). Although I did not recover a fourth buried soil at Vick’s (1988) core site MRS-3, Valentine (1992) and Clarke and Carver (1992) report two radiocarbon ages of 1600+/-40 and 1670+/-20 for a buried soil below the third youngest buried soil of Vick (1988), at Mad River Slough, core MRS-3. Based on previous studies and my observation, Soil Sd is laterally extensive over ca. 10km² along the margin of Arcata Bay.

Biostratigraphic data for the fourth youngest soil shows abrupt change from low marsh to tidal flat environments. Findings are indicative of rapid Coseismic subsidence of soils Sd.
In conclusion, three, estimated southern CSZ earthquake ages (years before A.D. 1950), from youngest to oldest are: A, 250; B, 1350 to 1190; C, 1290 to 1100; and D, 1590 to 1390, correlating to buried soils: Sa, Sb, Sc, and Sd. No evidence at any of the five Arcata Bay sites was found to support an earthquake at 820 cal year BP, suggested by Clark and Carver (1992) and Valentine (1992)."
Upper Holocene estuarine deposits of the Mad River Slough contain buried marsh surfaces that represent episodic, rapid subsidence events thought to be associated with coseismic deformation of the Freshwater syncline during large magnitude Cascadia subduction zone earthquakes. At the southern end of the Cascadia subduction zone, the fold and thrust belt associated with deformation of the accretionary margin swings easterly and extends onshore. Numerous compressional structures cross the region, deforming late Pleistocene and Holocene sediments. Northern Humboldt Bay is situated in a synclinal structure related to the active folding and faulting caused by the convergence of lithospheric plates.

Cyclic stratigraphic units of intertidal mud overlying peat deposits show episodes of rapid (coseismic) submergence and gradual emergence of the land surface relative to sea level during the late Holocene. Contacts between the peat and overlying mud are abrupt (<1 cm). The peat layers contain plant fossils indicative of high marsh (supratidal) environments, while the overlying mud contains plant fossils common to low and middle marsh (intertidal) environments.

At least four well-defined buried marsh surfaces are present in the southern portion of the slough, indicating four coseismic subsidence events. Preliminary radiocarbon dates show that a minimum of two paleoseismic events are recorded within the last 1,400 years, with two older events presently undated. The ages obtained for the earthquake-induced subsidence recorded at Mad River Slough are similar to the ages of other paleoseismic events in the vicinity of Humboldt Bay. Also, the physical characteristics and age of deposits in the Mad River Slough are similar to sequences of
buried marsh surfaces found along coastal Oregon and Washington. Within
the resolution limits of radiocarbon dating of past events, there appears to
be a correlation in the timing of earthquake-induced subsidence in coastal
Oregon and Washington and the deformation of the fold and thrust belt in
coastal northern California. This may indicate that a single large magnitude
earthquake generated along the Cascadia subduction zone is responsible for
simultaneous vertical crustal movement in Washington, Oregon, and northern
California.
Valentine, D. W., 1992, Late Holocene Stratigraphy, Humboldt Bay, California: Evidence
for Late Holocene Paleoseismicity of the Southern Cascadia Subduction Zone

Late Holocene Stratigraphy, Humboldt Bay, California: Evidence for Late
Holocene Paleoseismicity of the Southern Cascadia Subduction Zone
By
David Wade Valentine
ABSTRACT

Late Holocene stratigraphy representing rapid episodic subsidence is
found in synclines of Humboldt Bay, California. These synclines are
associated with the Cascadia subduction zone fold and thrust belt, which
bends eastward in Northern California. In the axes of the synclines, repeated
sequences of intertidal muds overlying saltmarsh to lowland peat deposits
represent episodes of rapid submergence followed by gradual emergence.
Observations of the contacts between the peats and overlying muds are
abrupt (<1 cm). The rapid submergence most likely represents coseismic
subsidence associated with large magnitude earthquakes. The evidence for
these submergence events is found within both the northern Freshwater
syncline and the southern South Bay syncline.

Radiocarbon dating indicates at least eight rapid episodic subsidence
events during the past 3500 years. Rapid episodic events have occurred for
the following age ranges: 0-300, 500-800, 1050-1350 (2 events), 1600-
1900, 2450-2600, 2800-3300, 3200-3400. There are indications of additional events back to about 4300 years, with ages of 3700-3900 and 4000-4300. The age ranges of the subsidence events are similar to ages for paleoseismic events from the Little Salmon fault. The Humboldt Bay paleoseismic events may be a record of great earthquakes occurring on the megathrust of the underlying Cascadia subduction zone.
The coastal sand dunes of Humboldt Bay provide the foundation for one of the more unique environmental niches in Humboldt County. Dunes straddle the coast, in one form or another, from Clam Beach to Table Bluff, and protect Humboldt Bay from wind and wave attack. The underlying geologic processes that form sand dunes, and hence dunes themselves, are very dynamic and this is reflected in the diversity of the types, location, and size of the sand dunes that we see along the coast. Dynamic as sand dunes are, they have a very limited geographic extent and their complex process of formation is quite susceptible to both natural and un-natural disturbances.

The dynamic variables that drive natural dune processes include: wind, longshore sand transport, sediment supply, sea level fluctuations, and vegetative cover which vary over time and affect the small and large scale dune forms that we see along the coast. Slowly changing variables such as sea-level fluctuations effect the dune field on a time scale of hundreds to thousands of years. In contrast, vegetative cover can change quickly and have profound effects on natural dune processes in tens of years or less.

The path sand takes to become incorporated into a large scale sand dune is complex and involves various stages of movement and temporary stability. The source of the sand is usually a local river or coastal bluff. The sand is then transported along the coast by wave action, a process called longshore drift. Longshore drift, along with daily tidal fluctuations, allows sand to be dried out by the summer winds and blown up onto the upper beach, where it can be incorporated into the dune system.

This paper is divided into 3 sections: 1) A description of basic dune features and the dune stratigraphy of the North Spit, 2) Age constraints on the dunes, and 3) Discussion.

BASIC DUNE FEATURES AND DUNE STRATIGRAPHY OF THE NORTH SPIT

The North Spit of Humboldt Bay (Figure 4-1) has extensive dune fields which exhibit many of the classic characteristics of typical coastal dunal landscapes; it also contains puzzling atypical stratigraphy which may reveal clues to the tectonic history of the Humboldt Bay region.

Like most of the other coastal dunes along the west coast of the United States, the introduction and subsequent invasion of non-native vegetation has had a profound affect on the natural dune morphology and processes on the North Spit (Figure 4-2). On the North Spit in particular, the non-native vegetation has stabilized or slowed the advancement of dunes and artificially raised the elevation of the foredune complex. This vegetation colonization has changed the dynamics of the dune field by reducing the amount of sand moving off the beach and into the dune field. Although the non-native vegetation affects the dune field, the coastal dune processes that were
operating thousands of years ago are still operating today, they’ve just been modified a bit.

**Foredunes and Deflated Surfaces**

By understanding the basic elements of coastal dune fields and their dynamic interaction with the beach, one can better hypothesize about the development of the older currently stabilized dunes on the North Spit, which may archive thousands of years of coastal development.

Two important and noticeable geomorphic features found on the western edge of the North Spit are the foredune and deflated surfaces (Figure 4-3). These geomorphic features are typical of coastal dune fields and they interact with and profoundly influence the development of the large scale sand dune fields to the east.

The first or primary foredune ridge marks the boundary between the generally active upper strand, where beach processes dominate, and the dune system, which is controlled by aeolian (wind) processes. The foredune of any dune field can be looked at as a machine that captures sand from the beach to feed inland sand dunes. The foredune on the North Spit is generally continuous and, because it is frequently trimmed by wave attack, runs parallel to the beach. Its presence, height and width are largely controlled by vegetation, which traps wind-blown sand moving off the beach.

Behind the primary foredune ridge is a series of older foredune ridges that form a zone of accumulated sand blown off

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**Figure 4-1.** Location map for the North Spit of Humboldt Bay dune field. The figure also shows $^{14}$C sample locations and anomalous gravel locations.
Figure 4-2. Arial images from the same section of the North Spit, 1942 (above) and 2000 (below). Among other things, the images show the dune advancement and vegetation development on the northern North Spit.
the beach which is slowly moving inland. This foredune complex, which varies in width, typically consists of complicated, hummocky topography and is the primary source of sand for dunes further inland. On the North Spit, the foredune is a topographically distinct feature, bounded on the west by the beach and on the east (inland) by deflated surfaces created by the last major episode of inland dune movement.

In areas where foredune sand deposits have been blown inland and removed down to the water table or below the level of the effective winds, deflation plains form, and erosion slows dramatically or ceases (Figure 4-3). These features can be seen in the multitude of seasonal wetlands that lie west of the large scale dunes. As with the dunes, these wetlands are constantly changing shape and extent in response to the slow inland migration of the growing foredune complex to the west, and as their inland margin migrates east at the trailing edge of the most recent dune movement.

Foredunes and deflated surfaces are common to most coastal dune fields and except for a few small details they operate in the same capacity everywhere. What makes every dune field unique is the depositional history of the dunes that develop landward of the active foredune/ deflated surface complex.

The Coastal Sand Dunes of the North Spit

East of the foredune/ deflated surface complex lay the most prominent dunes on the North Spit. The eastern portion of the dune field is highly stabilized and overgrown with a thick coniferous forest; the western portion of the dune field is more dynamic with new dunes forming at the coast. Currently there is an ongoing struggle between active advancing dunes and vegetative tenacity and colonization at the active/ stable dune interface (Figure 4-2).

The dunes on the North Spit are most obviously subdivided into three categories; stable, active, and erosional. The stable dunes tend to occupy the eastern edge of the spit, the active dunes are currently advancing from the western portion of the spit, while the erosional dunes are commonly found along the margins of the stable dunes where active dunes or tidal flats interface with the stable portions of the dune field.

The Stable dunes

The stable portion of the North Spit dune field resides along the western central portion of the spit where it interfingers with marsh and estuarine deposits to the east and younger dunes to the west (Figure 4-1). The stable portion of the dune field likely represents thousands of years of dune accumulation. Figure 4-3 shows the stabilized portion of the dune field is composed of successive parabolic dune pulses, each one stacking up against a previous dune pulse from east to west. At this time there is no reliable numerical data suggesting the time span between the successive pulses, although thermoluminescence dating techniques may offer some resolution.
Figure 4-3. Lidar image, (upper) with labels and geomorphic interpretation, (lower) of a portion of the North Spit dune field. This high quality image shows the classic coastal dune features, it also elucidates the complexity of the successive parabolic dune pulses.
The forested and stabilized dunes currently extend from Samoa to just south of Tyee City (Figure 4-1), but they clearly had a much greater extent. They are currently eroded on all sides and represent a fragment of a much more extensive dune field as is evidenced by the previously stable dune fragments that litter their less stable margins.

The eastern and western margins of the stable dune sequence are abnormally abrupt in some locations suggesting previous erosion from interaction with the estuary to the east and from the coast to the west. In many places on the western margin of the stable dunes, the tails of the youngest once stable parabolic dunes appear to be trimmed off in a shore parallel direction. On the eastern margin there is evidence suggesting the oldest dunes have been co-seismically submerged and subsequently had wetland soils develop on them (Leroy & Patton unpublished data, 2005).

**The Active Dunes**

The active dune advancement occupies the western portion of the North Spit and is currently advancing eastward over the older dunes. It is primarily advancing into the topographically low sections of the older dunes, but in areas of higher sand supply, or easier advancement, it has formed large dune sheets that cover vast tracts of land (Figure 4-2). In intermittent instances the active dunes have advanced over all the existing dunes and are currently advancing into the tidal marshes of the Mad River Slough to the east.

These active dunes are composed almost entirely of transverse sand dunes (Figure 4-2). Transverse dunes consist of a mass of highly mobile sand that is moving over the body of the larger sand mass. The long, sinuous, transverse sand dunes are oriented with ridge crests roughly perpendicular to the NW summer winds. Primarily because of their high rates of movement, these dunes are rarely vegetated except on their margins.

The foredunes and deflated surfaces to the east of the active dunes was the source area of the sand for those dunes, but because non-native vegetation has colonized the foredune, sand replenishment from the coast has been reduced. This is causing the active dunes to behave like a “slug” of sediment in some areas, moving over the existing dune field without replenishment of sand from the beach. Along the way it is incorporating sand from previously stable dunes, rather like cannibalizing its brethren in the process of forward movement.

At the eastern margin of the currently advancing dunes a battle is waging between the forest and the sea. Here the active dunes are burying a coniferous forest on the stable dunes. The forest consists mostly of spruce trees but other coastal conifer species are present. On the western margin of the advancing dunes, where the dunes are cannibalizing their brethren because they’re starving, and the dune sheet thins, the skeletal remains of previously consumed forests litter the landscape.
The erosional dunes

The most obvious areas of massive dune instability and erosion on the North Spit are the areas directly north and south of the stabilized and forested dune areas (This would be the areas south of the Mad River beach parking lot and from Samoa south). The erosional dunes are ones which had reached a degree of stability, and subsequently, for one reason or another, have become unstable and are in the process of erosion.

The margins of the currently stable dunes is the easiest place to observe these destabilized and eroding dunes, but careful observation will show that the stable dune field was considerably more extensive and that there are remnants of it miles from the currently forested sections. These areas are composed of previously stable dunes that are now in various states of morphologic alteration. As the dunes destabilize they become more susceptible to active dune encroachment and are either buried, partially eroded and incorporated into the active dune advancement, or both.

The erosional dunes are best recognized by their partial morphologic alteration. Remnants of the previously stable dunes typically consist of the partially eroded lateral edges of parabolic dunes. The erosional dunes span the entire spectrum of morphologic alteration. All of the erosional dunes have one thing in common, although they may be actively incorporated into the active dunes they are no longer moving as individual sand dunes.

Gravel deposits

There are gravel deposits found discontinuously along the western margin of the stable dunes between Manila and Tyee City (Figure 4-1). They are usually found as lag deposits on the deflated surfaces but they are often found residing directly on top of dune deposits. Preliminary measurements suggest some of these gravels are up to 38' above sea level, 100's of feet from the active coastline. Stratigraphic evidence suggests this gravel was emplaced on the western margin of the stable parabolic dunes and that it predates the currently active transverse dunes.

The gravel has unique characteristics which may provide evidence of its origin. The gravel is similar in physical characteristics to gravel currently found on the active beach. The gravel is abundant in all size ranges up to about 5 cm but rocks as big as 50 cm are not uncommon. It is smooth and almost exclusively blade and disk shaped although there are traces of rounded rocks, this could suggest the beach is the origin. In many places the gravel appears burned. Finally, The density of the gravel is difficult to ascertain due to the extensive vegetation and active dunes but it appears to thin inland from the deflated surfaces, again suggesting the beach was its origin.
DATING OF THE DUNES

Dating the Stabilized Dunes

As mentioned above the stable dunes are comprised of what appears to be a complex sequence of successive sand pulses, piled against each other. Currently there are no reliable criteria to distinguish the successive dune pulses from one another in the field. Subdividing the stable dunes into distinct units is difficult over their entire range because of local variations in the dune stratigraphy, patchy topographic data, and virtually impenetrable vegetative cover.

As you could imagine, dating of sand dunes is not a straight forward affair. Currently there are no reliable numerical dates that constrain the age of the stable dunes on the North Spit. Although there are no numerical dates, there are lines of reasoning suggesting the dunes are Holocene in age.

1) Personal observations suggest most Pleistocene geomorphic features in coastal Oregon and California, including marine terraces and sand dunes, have a wind blown silt cap deposited on them. This silt cap is absent on the dunes on the North Spit, suggesting they formed after the silt accumulated.

2) Soil development on the dunes is minimal (essentially just a Cox) compared to dunes of known Pleistocene age in Coastal Oregon which have more advanced soil development.

3) Some of the oldest dunes on the eastern margin have been submerged by co-seismic subsidence and have had wetland soils develop on them. Only a few examples of buried marshes older than 3000 years before present exist, and they are all quite deep in the stratigraphic column.

Dating the active dune advancement

Precision carbon 14 dating techniques and advanced data analysis were used to better constrain the age of the active dune sequence on the North Spit. Two Tree ring samples were taken from a tree that I believe was killed by advancement of the currently active dune migration. The tree was rooted in the tailing end of a partially eroded parabolic dune on the western margin of the stable dunes. The tree had been buried and later exhumed by advancement of a transverse dune sheet advancing with the currently active dune advancement. Tree ring data showed rapid ring growth until 10, give or take a few unknown number of years before its death, in which time the tree rings showed highly diminished growth. I interpret this diminished growth to slow burial and eventual killing by dune advancement.

Two samples were taken from the tree for atomic mass spectrometry (AMS) analysis. Distinct tree ring samples from both the inner portion and outer portion of the tree were sampled with a counted 70 growth years between them. Sample # NSTR 70 was the best preserved ring near the center of the tree, and sample # NSTR 1 was one of the last rings to show rapid growth before the vitality of the tree declined. The results
Due to fluctuations in the ratio of carbon 14 to other carbon isotopes over earth’s history, any carbon date can have multiple age ranges that are equally viable candidates for the actual age of the carbon sample. Knowing the exact number of years between two carbon samples can, in this case, help better constrain the age of tree death. Figure 4-5 shows that at the 94.5% confidence interval there are four viable age ranges for carbon sample NSTR 70 and 2 for sample NSTR 1. When the sample age ranges from sample NSTR 70 are shifted 70 years forward in time (remember this is the known number of years between the ring samples) then the age ranges for the sample should represent the year the tree was first inundated by sand from the advancing active dune sequence (Figure 4-5). The darkest areas, in the center timeline, on the lower portion of figure 4-5 show the age ranges in calendar years that are compatible with both carbon samples from NSTR 1 projected from below and NSTR 70 projected from above.

The results of this are that there are three distinct time ranges that could represent the calendar year the tree was initially inundated by advancing sand dunes. These are represented by the darkest boxes in figure 4-5. The age ranges are 1725-1790, 1805-1885, and 1915-1960. Of these three age ranges the most likely candidate is 1725-1790. The two later age ranges are either close to or post European settlement and have been discounted as likely candidates because historic literature suggests the dunes on the North Spit likely had a configuration similar to their present one then.

Depending on dune advancement rates, and vegetative tenacity, the 1725-1790 inundation time range is compatible with the 1700 Cascadia Subduction Zone event being the driving mechanism initiating the current dune advancement.
Sample NSTR 70 (190+/−40) shifted 70 years forward in time with the 95.4% probability age ranges projected down.

Overlap areas are the dates compatible with both samples death age ranges 1725-1790 1805-1885 1915-1960

Sample NSTR 1 (160+/−40) with the 95.4% probability age ranges projected up

Calibrated age ranges for sample NSTR 1 (160+/−40)

Calibrated age ranges for sample NSTR 70 (190+/−40)

Figure 4-5. This figure shows a slightly advanced way of analyzing 14C dates from trees. By using multiple 14C dates with known ages between them, one can better constrain the age of tree death. The upper portion displays the original lab results from figure 4-4. The lower portion displays the results after sample NSTR_70 is shifted forward in time to reflect the death age of the tree. The center lower time line shows the tree death age ranges compatible with both dated tree rings (the dark areas).
DISCUSSION

Overall understanding of the coastal sand dunes on the North Spit is continuously evolving but current observations suggest eustatic sea-level rise and local and regional tectonic processes may all play a part in the long and short term development of the dunes.

Over the long term, the dunes appear to be part of a transgression where the dunes are advancing over the existing estuary environment, possibly driven by Holocene sea level rise. Evidence from air photo interpretation suggests the dunes stack up, until larger advancements “punch through or over” the existing dune field and advance into the estuary. This leaves a corridor for future dune advancements to penetrate deeper into the pre-existing dune field where the process of dune stacking starts over again. The sum of this process repeating itself in intermittent sections of the dune field, over time, constitutes the transgression. One could see how this kind of dune advancement could bewilder the scientist trying to date the entire dune field.

On the short term, the dunes on the North Spit appear to archive evidence for both co-seismic subsidence and tsunamis. The South Manila core transect in figure 3-1 shows a submerged wetland soil lapping up onto the remnant of a lateral edge of a parabolic dune. The soil indicates the dune had been rapidly submerged since its original stabilization. Further investigations of the western margin of the stable dunes may elucidate a unique interaction between the dunes and the estuary during co-seismic subsidence events.

Evidence for tsunami inundating or over topping the North Spit dune field is mounting, but is not equivocal. The strongest evidence lies in the gravel that occupies the western margin of the stable dune sequence. The fact that this gravel is residing directly on top of sand dune deposits is hard to explain by any other mechanism besides tsunami. Other possibilities include Storm wave deposits, Native American Archeology sites, and abandoned beach deposits. Each of these alternatives has problems associated with them that lead one back to tsunami as the simplest mechanism that is not contradicted by the evidence.

Both storm waves and abandoned beach deposits are thought to be to uniform and sustained to deposit gravel on a sand dune to the extent we observe on the North Spit without entirely destroying the dune morphology. Particularly for the gravel that is found directly on dune stratigraphy in protected mid dune areas, storm waves can be ruled out and tsunamis seem to be the logical mechanism of deposition.

The sheer abundance and size distribution of the gravel suggests Native Americans did not import it to the North Spit, although they most certainly took full advantage of the gravel that was there (especially the larger rocks).

If the gravel was deposited by a tsunami, then it is likely that the tsunami pummeled the existing coastline and initiated the currently active dune advancement
by destabilizing the western margin of the spit. Therefore there may be further evidence in the dune geomorphology of the margins of the stable dunes to support the conclusion that the north spit has been inundated by a tsunami (Figure 4-6).

Hold on, this is where speculation really starts to pick up, but after seeing some of the video footage from Indonesia nothing would surprise me.

The abrupt termination of the northern, western, and southern margins of the stable dune field is suspicious. Not that one wouldn't expect erosion on the edge of a stable dune field, but the abruptness of it seems anomalous.

On the western edge the abrupt termination is often coincident with the anomalous gravel. On the northern edge, the dune field dwindles into the “skeletonized” framework of the once stable pre-existing dune field now littered with gravel.

Finally, the southern termination of the stable dune field is very abrupt. There is evidence that the stable dunes continued south, but only fleeting remains of the once stable dunes persist. It is plausible that the southern end of the North Spit was overtopped or heavily inundated during the most recent tsunami eroding the dunes from Samoa south.

There are two or three large arcuate shaped areas where the active dunes have advanced quite deeply into the stable dune field.
(Figure 4-6). It’s within the realm of possibilities that these areas represent exceptionally deep run-up scallops on the western margin of the spit. This would destabilize the surface of the existing dunes and allow for expedited dune advancement.

Based on the estimated age of the currently advancing dunes it is likely that they initiated close to the 1700 Cascadia Subduction Zone event. If this is the case, then the gravel deposits were likely deposited during the 1700 tsunami event that has been recorded around the entire Pacific Ocean including Humboldt Bay.

Finally, the currently active transverse type dunes appear to be in sharp contrast to the consistently parabolic type dunes that preceded them presumably for thousands of years. This could be attributed to the possibility that the current dune advancement is the only one initiated by a Tsunami. Therefore the other tsunamis that have inundated the Humboldt Bay region are likely from events which did not create tsunamis of the magnitude seen in the 1700 event. This hypothesis along with the fact that the 1700 event is the only consistently correlated event in the Humboldt Bay region could suggest the rupture of the Southern Cascadia Subduction Zone is not always coincident with the rupture of the more northern segment. This may suggest the rupture of the entire Cascadia subduction zone (such as is thought to be the case for the 1700 event) may be the exception and not the rule and that the southern Cascadia subduction zone has a mostly independent rupture history.

Further research is needed to work out the development of the North Spit and to test some of the above hypothesis. Future research projects include high precision GPS mapping of the gravel deposits, further investigation of the eastern margin of the dunes where they interstratify with the estuary environment, and hopefully a thermoluminescence campaign to obtain some numerical dates on the stable dunes.
Stop #1: At stop #1 Jay will give a brief overview of the Holocene stratigraphy of Humboldt Bay and why paleoseismologists believe it is significantly influenced by the earthquake cycle of the Cascadia Subduction Zone. Tom will give an overview of the South Spit dune stratigraphy, the South Bay core transect and start our discussion on tsunami inundation of Humboldt Bay. Jay will then give an overview of the research conducted in the Eel River Delta.

In 1992, Chinese exchange student Wen-Hao Li cored most of the lower Eel river delta and reported 5 cycles of inter-tidal sedimentation punctuated by sudden submergence. In his thesis, Lee briefly mentions that cores from the portion of the delta you are overlooking may have archived tsunami deposits. Further in the background, closer to the axis of the valley, Carver has reported submerged spruce forests dated at the late 1800’s. This will be discussed.

View right: Table Bluff terraces. Carver and Burke (1992) report the ages of the terraces blanketing Table Bluff as 83k, 103k, 120k, and 200k ybp. Stop #1 is on the 83k terrace, we then traverse the 103k and clip the northern edge of the 120k.

Stop #2: Jay Patton will give us an overview of the Holocene stratigraphy of Hookton Slough and summarize the current evidence for tsunami inundation of southern Humboldt Bay.

Turn left out of the parking lot and head back to 101 north. The Hookton Slough core transect starts at the edge of the parking lot and extends east approximately 5 miles. The eastern termination of the Hookton slough core transect was just west of the row of trees you see in the foreground to your left.
<table>
<thead>
<tr>
<th>Running Mileage</th>
<th>Distance</th>
<th>Spectacle of interest</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4-5.1</td>
<td>0.5</td>
<td>Salmon creek</td>
<td>Salmon Creek has repeatedly overtopped this bridge, furthermore there's an unconfirmed anecdotal story of bay waters inundating the town of Beatrice near this location.</td>
</tr>
<tr>
<td>5.5-5.2</td>
<td>0.1</td>
<td>Left turn</td>
<td>Intersection with Eel River road, go left, but do not get on the freeway heading south, head up over the overpass.</td>
</tr>
<tr>
<td>5.8-5.4</td>
<td>0.2</td>
<td>Veer right</td>
<td>Go right at the road intersection and get on Highway 101 heading north. The view at the intersection is the Salmon Creek valley, location of Carver and Burkes investigation of the Little Salmon Fault in 1988.</td>
</tr>
<tr>
<td>6.0-5.7</td>
<td>0.3</td>
<td>Little Salmon core and trench site</td>
<td>To your right is the Witter and others Little Salmon fault investigation site. The site lies in a depression, on the other side of the tree line that is midway between the freeway and the base of the hillside</td>
</tr>
<tr>
<td>7.2-6.8</td>
<td>1.1</td>
<td>College of the Redwoods fault investigation</td>
<td>LACO Associates has conducted extensive fault investigations for the College of the Redwoods.</td>
</tr>
<tr>
<td>8.2-7.7</td>
<td>0.9</td>
<td>Old mouth of Salmon Creek</td>
<td>The slough you see on your left is the old mouth of Salmon Creek.</td>
</tr>
<tr>
<td>8.8-8.3</td>
<td>0.6</td>
<td>South Spit</td>
<td>To the left, on the horizon, is the topographically low South Spit, obviously vulnerable to tsunami overtopping.</td>
</tr>
<tr>
<td>9.7-9.2</td>
<td>0.9</td>
<td>Fields Landing</td>
<td></td>
</tr>
<tr>
<td>10.4-10</td>
<td>0.8</td>
<td>King Salmon, PG&amp;E power plant</td>
<td>King Salmon is already vulnerable to flooding and could be effected by moderate to large tsunamis. PG&amp;E has conducted numerous studies of earthquake and tsunami vulnerability for its King Salmon power plant site. They have also been the benefactor of numerous masters theses at Humboldt State University.</td>
</tr>
<tr>
<td>11.8-11.1</td>
<td>1.1</td>
<td>Elk River Valley, Marine terraces</td>
<td>To the north east you can see the flight of marine terraces bounding the northern edge of the Elk River Delta. Carver and Burke (9192) report the ages of the two lowest terraces in this vicinity as 83k and 120k.</td>
</tr>
<tr>
<td>14.2-13.2</td>
<td>2.1</td>
<td>Sea cliff to right Bayshore Mall to the left</td>
<td>To the left is the Bayshore mall, the parking lot is built on mud and may be vulnerable to liquefaction during hard ground shaking, to the right is a terrace back edge, Carver and Burke (1992) report the age of the terrace above the Bayshore mall as 64k. Behind the mall is where 85% of Humboldt County gasoline is pumped from tankers. The gas will likely be entrained in one form or another in any moderate to large tsunami, and in a worse case scenario, flood the pandemonious mall parking lot with flaming petroleum products.</td>
</tr>
<tr>
<td>15.9-15.1</td>
<td>1.9</td>
<td>Broadway turns to 5th st.</td>
<td></td>
</tr>
<tr>
<td>15.5</td>
<td>0.4</td>
<td>Terrace Riser</td>
<td>Carver and Burke Report this as the riser to the 83k terrace.</td>
</tr>
<tr>
<td>15.9</td>
<td>0.4</td>
<td>Terrace Riser</td>
<td>Get into left lane and prepare to turn left onto R st. towards route 255 to Samoa</td>
</tr>
<tr>
<td>Running Mileage</td>
<td>Distance</td>
<td>Spectacle of interest</td>
<td>Notes</td>
</tr>
<tr>
<td>----------------</td>
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<td>-------</td>
</tr>
<tr>
<td>17.1-16.1</td>
<td>0.2</td>
<td><strong>Left turn</strong></td>
<td>Turn Left onto R st., and proceed across hwy. 101 S. and drive over the Bridge.</td>
</tr>
<tr>
<td>17.5-16.3</td>
<td>0.2</td>
<td>Samoa Bridge</td>
<td>Samoa Bridge is currently undergoing seismic retrofit. The bridge currently has temporary seismic induced barricades.</td>
</tr>
<tr>
<td>17.7-16.5</td>
<td>0.2</td>
<td>Woodley island</td>
<td>View left is Woodley Island</td>
</tr>
<tr>
<td>18.0-16.8</td>
<td>0.3</td>
<td>Indian Island massacre site</td>
<td>The site was at the far end of the visible island</td>
</tr>
<tr>
<td>18.8-17.6</td>
<td>0.8</td>
<td>View of forested stable sand dunes ahead</td>
<td></td>
</tr>
<tr>
<td>19.2-18.1</td>
<td>0.5</td>
<td><strong>Right turn</strong></td>
<td>Turn right at the T-bone intersection after the bridge and proceed on Samoa Blvd.</td>
</tr>
<tr>
<td>19.8-18.8</td>
<td>0.7</td>
<td>South Manila core transect</td>
<td>In the low lying marsh to the left is the location of the S. Manila core transect, the transect starts where the forested dunes meet the marsh and ends where the road fill meets the marsh on the western side of the road.</td>
</tr>
<tr>
<td>22.4-21.1</td>
<td>3.3</td>
<td><strong>Caution!</strong></td>
<td>As you proceed get ready to park at the mouth of the Mad River Slough. Parking here may be a little tricky, there’s plenty of space its just that almost all of it is on the other side of the road. There is parking space on both sides of the bridge, but watch out for high speed maniacs when your crossing the road. If you overshoot, you can turn left on Jackson Ranch road .8 miles down the road and safely turn around and head back, parking should then be easy, although your mileage will be even further confusing.</td>
</tr>
<tr>
<td>22.4-21.1</td>
<td>0</td>
<td><strong>Stop #3</strong></td>
<td><strong>Stop #3:</strong> Tom will give an overview of the Holocene stratigraphy of Northern Humboldt Bay and Jay will give a more detailed overview of the research conducted here in the Mad River Slough. We will then collect a core sample and see if we can repeat the stratigraphic column reported for this location by Vick in 1988, and Pritchard in 2005.</td>
</tr>
<tr>
<td>23.3-21.9</td>
<td>0.8</td>
<td><strong>Left turn</strong></td>
<td>Turn left on Jackson Ranch Road and follow the sometimes winding road into the Arcata bottom lands.</td>
</tr>
<tr>
<td>25.3-23.9</td>
<td>2</td>
<td><strong>Left turn</strong></td>
<td>Turn left on Seidel road</td>
</tr>
<tr>
<td>26.3-24.9</td>
<td>1</td>
<td><strong>Right turn</strong></td>
<td>Turn right on Lanphere road</td>
</tr>
<tr>
<td>26.8-25.1</td>
<td>0.2</td>
<td><strong>Left turn</strong></td>
<td>Turn left on Mad River road</td>
</tr>
</tbody>
</table>

**Captured wetlands**The margin of Humboldt Bay was dominated by expansive wetlands before European settlement. The current wetlands represent only a fraction of the original coastal marsh because diking has captured the bottom lands for agriculture. The sloughs and dry channels you see over the next .5 mile are remnants of these tidal wetlands. The forested dunes you see to the left are stabilized parabolic dunes adjacent to the Mad river slough.
<table>
<thead>
<tr>
<th>Running Mileage</th>
<th>Distance</th>
<th>Spectacle of interest</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.7-28.2</td>
<td>3.1</td>
<td>Tyee City and Mad River</td>
<td>This little community out here is called Tyee City. The levy to the right was over topped in the 1997 floods and provides little protection against the merciless Mad River.</td>
</tr>
<tr>
<td>30.1-28.4</td>
<td>0.2</td>
<td>Mad River Fault</td>
<td>Looking down stream, on the right bank, you can see where the Mad River has cut a nice cross section across the southern branch of the Mad River Fault.</td>
</tr>
<tr>
<td>32.5-28.8</td>
<td>0.4</td>
<td>Stop #4</td>
<td>Stop #4: Tom will discuss the sand dune stratigraphy of the North Spit and we will observe anomalous gravel deposits in the sand dunes which are interpreted to be Tsunami deposits. This is the end of the official part of the Field trip, however the Six Rivers Brewery provides a good view of the Arcata Bottom lands and is an excellent place to discuss the days events, therefore, any one who is interested may join us at the Brewery.</td>
</tr>
</tbody>
</table>

Turn around and head back down Mad River road.

<table>
<thead>
<tr>
<th>Mileage</th>
<th>Distance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.5</td>
<td>2.7</td>
<td>Left turn</td>
</tr>
<tr>
<td>32.2</td>
<td>0.7</td>
<td>Right turn</td>
</tr>
<tr>
<td>32.6</td>
<td>0.4</td>
<td>Left turn</td>
</tr>
<tr>
<td>32.9</td>
<td>0.3</td>
<td>Traffic circles</td>
</tr>
<tr>
<td>33.9</td>
<td>1</td>
<td>Exit Freeway</td>
</tr>
<tr>
<td>34.6</td>
<td>0.6</td>
<td>Six Rivers Brewery</td>
</tr>
</tbody>
</table>

Turn Right into the Brewery’s parking lot. Six Rivers Brewery has been a huge benefactor in Tsunami relief and education.
REFERENCES

Abramson, H., 1998. Evidence for Tsunamis and Earthquakes During the Last 3500 Years from Lagoon Creek, a Coastal Freshwater Marsh, Northern California: M. S. thesis, Arcata, California, Humboldt State University, 76 p.


Leroy, Thomas H., 1999, Sand Dune Stratigraphy and Paleoseismicity of the North and South Spits of Humboldt Bay, Northern California: M.S. thesis, Arcata, California, Humboldt State University, Department of Geology, 37 p.

Li, Wen-Hao, 1992, Evidence for the late Holocene coseismic subsidence in the lower Eel River Valley, Humboldt County, northern California: an application of foraminiferal zonation to indicate tectonic submergence: M.S. thesis, Arcata, California, Humboldt State University, Department of Geology, 87 p.


