Regional tectonic deformation of the northern Oregon coast as recorded by Pleistocene marine terraces

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Title: Regional Tectonic Deformation of the Northern Oregon Coast as Recorded by Pleistocene Marine Terraces.

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Pleistocene marine terraces of the northern Oregon coast are an important factor in understanding the tectonics and paleoseismicity of the central Cascadia subduction zone. The lowest marine terrace, tentatively correlated to 80,000 year old Whiskey Run terrace of southern Oregon, is intermittently exposed in the present day sea cliff along an
80 km section of coastline between Tillamook Head and Cape Kiwanda. Terrace sediments consist largely of fine material such as clay, silt and fine sand with several locations containing large amounts of gravel derived from nearby headlands and steep bedrock hills. The terrace sediments are interpreted to be deposited in back-barrier marine environments, such as a bay, very similar to the bays which presently exist on the northern Oregon coast. Interbedded with terrace sediments are peat horizons which represent buried marsh or forest surfaces. These peat horizons have gradational lower contacts and abrupt upper contacts with terrace sediments indicating that the marsh or forest surfaces formed gradually above sea level and were suddenly downdropped below sea level to be buried by bay sediments. Such features are consistent with a seismically active Cascadia subduction zone which produces interseismic coastal uplift and coseismic coastal subsidence.

Elevations taken on the lowest terrace surface show little uplift (11-20 ± 3 m above MSL) and very little variation in uplift along the coast when compared to other locations on the Oregon and Washington coast. Terrace sediments at all locations show no evidence of tilting which also indicates that the terrace has not undergone any significant folding or faulting. Because of the low uplift rate on the northern Oregon coast the wave-cut platform of the lowest terrace, where it is cut into soft Tertiary
marine sediments, is not exposed and is likely being reoccupied by the present high sea level stand. The lack of significant deformation on the northern Oregon coast is probably due to its tectonic setting (trench-parallel and 120 km from the trench) causing the subducting Juan de Fuca plate to be deeper along the northern Oregon coast than elsewhere along the Cascadia margin.
REGIONAL TECTONIC DEFORMATION OF THE NORTHERN OREGON COAST
AS RECORDED BY PLEISTOCENE MARINE TERRACES

by

RICHARD ALAN MULDER

A thesis submitted in partial fulfillment of the requirements for the degree of

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TO THE OFFICE OF GRADUATE STUDIES:

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Geologic Problems and Purpose of Investigation</td>
<td>4</td>
</tr>
<tr>
<td>Study Area</td>
<td>11</td>
</tr>
<tr>
<td>Background</td>
<td>13</td>
</tr>
<tr>
<td>Previous Work</td>
<td>17</td>
</tr>
<tr>
<td>METHODS OF INVESTIGATION</td>
<td>22</td>
</tr>
<tr>
<td>RESULTS</td>
<td>28</td>
</tr>
<tr>
<td>Descriptions of Individual Terrace Segments</td>
<td>29</td>
</tr>
<tr>
<td>Diatoms in Terrace Sediments</td>
<td>54</td>
</tr>
<tr>
<td>Age and Correlation of the Lowest Terrace Surface</td>
<td>54</td>
</tr>
<tr>
<td>Elevation and Tectonic Deformation of Terraces</td>
<td>59</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>64</td>
</tr>
<tr>
<td>Depositional Environment of Terrace Sediments</td>
<td>64</td>
</tr>
<tr>
<td>Age of the Lowest Terrace Surface</td>
<td>75</td>
</tr>
<tr>
<td>Correlation of the Lowest Terrace Surface</td>
<td>76</td>
</tr>
<tr>
<td>Tectonic Deformation of Terraces</td>
<td>77</td>
</tr>
<tr>
<td>CONCLUSIONS AND FUTURE STUDIES</td>
<td>84</td>
</tr>
</tbody>
</table>
LIST OF TABLES

TABLE       PAGE
I  Descriptions of Soils on The Lowest
      Terrace Surface......................  57
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>Description</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cascadia Subduction Zone Showing Area of Study on the Northern Oregon Coast</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>(after Riddihough, 1984)</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Map of the Northern Oregon Coast Displaying Locations of Towns, Beaches,</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Headlands, and Bays</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Recently Mapped Folds and Faults Off the Northern Half of the Oregon Coast</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>(from Goldfinger et al., 1992)</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Schematic Sea Level and Coastal Uplift Curves During the Time of an</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Interglacial High Sea Level Stand (After Bradley and Griggs, 1976)</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Conceptualized Cross Section Through a Marine Terrace on the Northern</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Oregon Coast (after Kerms, 1977)</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Sea Level Curve Derived From Uplifted Coral Reefs From the Huon Peninsula,</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>New Guinea (After Chappell and Shackleton, 1986)</td>
<td></td>
</tr>
<tr>
<td>Chapter</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>7</td>
<td>Stratigraphic Sections From the Indian Beach, Arcadia Beach, and Hug Point Terrace Segments</td>
<td>31</td>
</tr>
<tr>
<td>8</td>
<td>Indian Beach Terrace Containing Alternating Layers of Gray Mud and Black Peat</td>
<td>32</td>
</tr>
<tr>
<td>9</td>
<td>Stratigraphic Sections From the Arch Cape, Cove Beach, and Short Sand Beach Terrace Segments</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>Cove Beach Terrace Showing the Slope Retreat Which is Common to Many Terrace Segments</td>
<td>37</td>
</tr>
<tr>
<td>11</td>
<td>Liquefaction Features From the Cove Beach Terrace Segment</td>
<td>39</td>
</tr>
<tr>
<td>12</td>
<td>North Cape Meares terrace</td>
<td>41</td>
</tr>
<tr>
<td>13</td>
<td>Stratigraphic Section From the North Cape Meares Terrace Segment</td>
<td>42</td>
</tr>
<tr>
<td>14</td>
<td>Stratigraphic Sections From the Netarts Bay Terrace Segment (See Figure 15 for locations): (a) Just North of Wee Willies; (b) Just North of the Fish Hatchery; (c) About One-Half km South of the Fish Hatchery</td>
<td>45</td>
</tr>
</tbody>
</table>
15. Map of Netarts Bay Showing the Locations of
the Three Drill Sites (Black Dots) plus
Wee Willies and the Whiskey Creek Fish
Hatchery................................. 46
16. Stratigraphic Sections Compiled From Drill
Cores at Netarts Bay...................... 47
17. Possible Thrust Fault (Dashed Line) Just
North of Happy Camp.................... 49
18. Stratigraphic Sections From the Cape Lookout
and Cape Kiwanda Terrace Segments........... 51
19. Cape Lookout Terrace Containing a Large
In Situ Tree Trunk............................ 52
20. Soil Profile from the Hug Point Terrace
Segment Typical of Soils on the Lowest
Terrace Surface............................ 58
21. Elevation With Error Bars of the Lowest
Terrace Surface Along the Northern
Oregon Coast............................. 60
22. Stratigraphic Cross Section From an Outcrop
at Netarts Bay Between Wee Willies
and the Whiskey Creek Fish Hatchery
(See Figure 15)............................. 62
23. Peat Layer from Netarts Bay Showing Gradual
Lower Contact and Abrupt Upper Contact
with Bay Mud............................... 67
24. Diagrammatic Sketch of Continental Deformation During Interseismic (Top) and Coseismic (Bottom) Periods (After Ando and Balazs, 1979) ........................................ 68

25. For a marsh surface to be buried by intertidal sediments there needs to be at least 1 to 2 m of coastal subsidence or rise in sea level (or vice versa) ....................... 70

26. Different Environments Around Netarts Bay Including Lowland Forest, Salt Marsh, and Tidal Flat .................................................... 72

27. Elevation Picks on the Lowest Marine Terrace in Washington and Extreme Northern Oregon .................................................. 79
INTRODUCTION

The Oregon and Washington coastlines lie near the boundary between the North American plate and the subducting Juan de Fuca plate (Figure 1). Underthrusting along this boundary is susceptible to megathrust dislocation events (Mw 8+ earthquakes) causing permanent vertical deformation of the coastline (West and McCrumb, 1988). Long term uplift along such coasts is usually recorded by elevated marine terraces. These terraces provide a reference datum which can be used to determine temporal and spatial variability of coastal tectonic deformation (McInelly and Kelsey, 1990).

This study focuses on Pleistocene marine terraces of the northern Oregon coast between Tillamook Head and Cape Kiwanda (Figure 2). This segment of coastline contains one fairly continuous terrace which is examined to determine the rates and styles of deformation during the late Quaternary. The terrace is also unique in that it records short term up and down tectonic movements along with long term uplift. The combination of long term uplift and jerky short term deformation seen in the terraces of the northern Oregon coast is indicative of an active subduction zone.
Figure 1. Cascadia subduction zone showing area of study on the northern Oregon coast (after Riddihough, 1984).
Figure 2. Map of the northern Oregon coast displaying locations of towns, beaches, headlands, and bays.
GEOLOGIC PROBLEMS AND PURPOSE OF INVESTIGATION

While it is well established that the Juan de Fuca-Farallon oceanic plate has been subducting beneath the northwestern part of the North American plate for the last 40 million years (Atwater, 1970; Riddihough, 1984) the nature of the subduction process in the late Quaternary is widely debated (Ando and Balazs, 1979; Heaton and Kanamori, 1984; Atwater, 1987; Darienzo and Peterson, 1990; Goldfinger et al., 1992). Evidence for subduction comes from offshore magnetic anomalies which indicate a Quaternary convergence rate of 3-4.5 cm/yr (Heaton and Hartzell, 1987). However, magnetic anomaly data is unable to resolve the present status of subduction (Ando and Balazs, 1979; Spence, 1989). Has underthrusting on the Cascadia subduction zone recently ceased with the two plates becoming locked together? Is subduction presently occurring, either aseismically, or accompanied by large infrequent thrust earthquakes along the boundary between the two plates or is intraplate deformation within the overriding North American plate taking up much of the oblique convergence (Goldfinger et al., 1992)? Since magnetic anomalies cannot answer these questions, research must turn to recent geologic, seismic, and deformational features caused by convergence (or lack of it) to determine the nature of present plate interactions (Spence, 1989).
Early evidence which indicated ongoing subduction included the identification of a Benioff zone (Tabor and Smith, 1985), modern coastal vertical and horizontal deformation (Ando and Balazs, 1979; Reilinger and Adams, 1982; Adams, 1984; Savage et al., 1981), and seismic activity on offshore fracture zones that indicate a rate of plate motion similar to rates determined from magnetic anomalies (Hyndman and Weichert, 1983). Yet, the lack of any large or small thrust earthquakes in historic times along the interface between the Juan de Fuca and North American plates provides a strong argument against active subduction accompanied by strong coupling between the two plates (Tabor and Smith, 1985; Heaton and Hartzell, 1986). However, several subduction zones around the Pacific have been seismically quiescent before large thrust earthquakes (Rogers, 1988).

Ando and Balazs (1979) and Reilinger and Adams (1982) used repeated geodetic level surveys and tide gauge measurements to show a consistent landward tilting of the Washington and Oregon coast ranges. These authors have interpreted these data to indicate ongoing subduction through aseismic creep. Aseismic subduction is also supported by a young, warm, oceanic crust which may not be able to support elastic strain accumulation along the subduction interface, and by a thick sediment cover above the oceanic plate which may be lubricating the subduction
process (Davis et al., 1990; Bryne et al., 1988). It has also been noted that the Washington and Oregon coast lacks uplifted Holocene terraces, a common feature on coastlines with seismically active subduction zones (West and McCrumb, 1988).

Heaton and Kanamori (1984) compared the Cascadia subduction zone with several other subduction zones and found many similarities in the physical features of Cascadia and strongly coupled subduction zones (Chilean types). These features include a young oceanic crust, an inactive back-arc basin, a Benioff zone that dips at about 10-15 degrees and does not extend beyond 100 km depth, a shallow trench, a topographically smooth oceanic crust, and an ominous seismic quiescence, presumably before a major thrust event. Furthermore, subduction zones which are aseismic (Mariana type) are usually characterized by old oceanic crust. This comparison indicates that great subduction zone earthquakes are a possibility in the northwest.

It has not been until the late 1980's that persuasive geologic evidence has been reported to indicate that the Cascadia subduction zone is active and has been producing megathrust earthquakes in late Quaternary time. Much of this evidence has come from Holocene salt marsh stratigraphy in Washington and Oregon coastal bays (Atwater, 1987; Darienzo and Peterson, 1990; Darienzo, 1991). These marshes contain multiple buried peat layers (old marsh surfaces)
capped by tsunami generated sand layers and intertidal mud. Such stratigraphy is probably created by periods of interseismic strain accumulation which causes coastal uplift and marsh formation followed by seismic strain release which causes sudden subsidence and marsh burial. Similar marsh stratigraphy and subduction zone deformation has been witnessed before and after large megathrust events in Chile and Alaska (Plafker, 1972 and 1990).

Radiocarbon dates of buried marsh surfaces in Washington and Oregon, although containing large margins of error, cannot be shown to be uncorrelated (Atwater and Yamaguchi, 1991, and Darienzo and Peterson, 1991). This is particularly true of the last event which occurred approximately 300 years ago. This date has also been constrained by ring-width pattern matching (Yamaguchi et al., 1989) and high precision radiocarbon dating of outer tree rings (Atwater and Yamaguchi, 1991) to determine death dates for buried trees in coastal bays along southwestern Washington.

Further evidence for large scale seismic events comes from turbidite deposits in deep sea channels off Oregon and Washington. Adams (1990) examined deep sea sediment cores and found thirteen turbidite deposits in two of the tributaries of the Cascadia Channel above volcanic glass deposits from the Mt. Mazama eruption (6845 ± 50 radiocarbon years before present). He also found thirteen turbidite
deposits in the lower part of the main Cascadia Channel instead of twice that number that should be present if turbidity currents from the two tributaries had occurred at different times. In addition, Adams (1990) found thirteen turbidite deposit above Mt. Mazama ash in the Astoria Canyon and at two sites off Cape Blanco. The only reasonable explanation for the occurrence of identical numbers of turbidites at several different localities are large events which trigger the turbidity currents synchronously.

Savage et al. (1981) and Savage and Lisowski (1991), interpreted geodetic data from Seattle, Richland, and the Olympic Peninsula of Washington to show a maximum contraction in a direction which is nearly parallel to the northeast plate convergence direction. They consider the upper plate deformation in these areas to be consistent with elastic strain accumulation from a presently coupled Cascadia subduction zone. This implies that large thrust earthquakes should be expected in Washington in the future.

Recent mapping offshore of the central and northern Oregon coastline has shown the presence of large scale structural features such as strike-slip faults and folds (Figure 3) which deform Pleistocene and Holocene marine sediments (Goldfinger et al., 1992). Many of these structures project onshore to known Tertiary structures, but the activity of these onshore structures during the Quaternary has yet to be proven. It has also been
Figure 3. Recently mapped folds and faults off the northern half of the Oregon Coast (from Goldfinger et al., 1992).
speculated that many of the bays on the northern Oregon coast are formed in synclines similar to South Slough near Coos Bay. Active downwarping on these structures during interseismic periods on the subduction zone may be responsible for the buried marsh surfaces within the bays. Alternatively, deformation on the structures may occur only during megathrust events. Goldfinger et al. (1992) have further speculated that deformation along the structures they have mapped may be accommodating much of the convergence along the subduction zone.

These studies raise questions regarding the nature of subduction and its tectonic signature on the Cascadia subduction zone. Pleistocene marine terraces, because they record past sea levels, provide a reference surface which can be used to determine long term coastal deformation. Furthermore, if the Cascadia subduction zone has been seismically active during the Holocene (as indicated by salt marsh stratigraphy), then it was likely active during the Pleistocene. Evidence indicating such activity should be recorded in Pleistocene deposits. Thus, the objectives of this thesis are to (1) map Pleistocene marine terraces on the northern Oregon coast between Tillamook Head on the north and Cape Kiwanda on the south (Figure 2); (2) measure stratigraphic sections of terrace sediments at suitable sites to determine depositional environment and to record evidence which may indicate paleoseismic events such as
buried marsh surfaces (stacked peat sequences) or liquefaction features; (3) correlate the lowest terrace surface along this coastal segment; (4) use elevation surveys of the correlated terrace to determine late Quaternary regional coastal deformation; (5) measure repeated stratigraphic sections along a single outcrop to determine local deformation features; and (6) compare terrace deformation with geodetic strain data and mapped onshore and offshore large scale geologic structures to ascertain their compatibility. The results of this study should help in constraining models of subduction zone deformation and seismicity along the central Cascadia margin.

STUDY AREA

The study area is an 80 km section of coastline between Tillamook Head and Cape Kiwanda in northwest Oregon in the central Cascadia margin (Figures 1 and 2). This section of coastline runs north-south parallel to the trench which is located approximately 120 km offshore (Figure 1). South of the study area the trench becomes progressively closer to the coastline (Figure 1) until it reaches a minimum of 60 km at Cape Blanco. North of the study area, in northern Washington, the trench makes a fairly sharp bend (Figure 1) from a north striking trench to a north-northwest striking trench. This bend in the margin creates an arch or bulge in
the subducting Juan de Fuca plate beneath northern Washington (Crossen and Owens, 1987). This arch likely increases local frictional coupling with the overriding continental plate, leading to a wide accretionary prism, as reflected in the onshore melange units of the Olympic Peninsula. Thus, the present study area is located in between two different large scale tectonic regimes and is itself located within a third tectonic regime. This regime might represent the Cascadia coastline that is located the greatest distance from the deforming accretionary prism.

The location of the study area was chosen for several reasons: 1) detailed studies of the late Pleistocene marine terraces had not previously been performed in the area; 2) reconnaissance studies showed the presence of stacked peat sequences within terrace deposits (Peterson and Darienzo, 1988); and 3) it encompasses an area of known Holocene stacked peat sequences (Darienzo and Peterson, 1990; Darienzo, 1991).

The northern Oregon coast (Figure 2) is characterized by large resistant headlands (Tillamook Head, Arch Cape, Cape Falcon, Cape Meares, Cape Lookout, and Cape Kiwanda) separated by sandy or rocky beaches (Cannon Beach, Arcadia Beach, Cove Beach, Nehalem Spit, Rockaway Beach, Netarts Spit, and Tillamook Spit) and/or bays or estuaries (Nehalem Bay, Tillamook Bay, Netarts Bay, and Sand Lake). Major cities or towns in the study area include Cannon Beach,
The bedrock geology of the northern Oregon coast can be broken into two general units (Lund, 1972; Lund, 1974). The first unit is marine sedimentary rocks of Oligocene to middle Miocene age. The middle Miocene Astoria Formation, which consists predominantly of sandstone, siltstone, and shale makes up most of this unit. In addition, there are some unnamed strata of Oligocene to mid-Miocene age. The second unit consists of Miocene intrusive and extrusive basalt. These basalts are much more resistant than the sedimentary rocks and generally form the prominent headlands and sea stacks in the area. Conversely, the softer marine sediments are easily eroded to form the many wide beaches, bays, and coves on the northern Oregon coast.

BACKGROUND

Abandoned or relict Pleistocene marine terraces are common features on emergent coastlines (Lajoie, 1986). Pleistocene marine terraces were usually formed during interglacial high sea level stands at times when the rate of land emergence was approximately equal to the rate of sea level fluctuation (Figure 4) (Bradley and Griggs, 1976; Bull, 1984). This allowed a relatively long period of time for ocean waves to erode a well developed wave-cut platform. As sea level began to fall, the coastline continued to rise,
Figure 4. Schematic sea level and coastal uplift curves during the time of an interglacial high sea level stand (after Bradely and Griggs, 1976). Marine terraces are formed during the interval between the two arrows when sea level rise is approximately equal to the rate of coastal uplift.
and the platform became exposed and preserved. Alternatively, times of rapid relative sea level rise or fall did not allow sufficient time for well developed platforms to be carved.

Common features of marine terraces are shown in Figure 5. The wave-cut platform (or abrasion platform) is a gently seaward dipping platform formed by abrasion from ocean waves. Although referred to as a platform, relief up to several meters may be common (Bradley and Griggs, 1976), especially where there are sedimentary beds of alternating hardness. The platform is usually overlain by a veneer of marine sediments which may or may not be overlain by non-marine sediments. The point at which the wave-cut platform meets the steeply sloping sea cliff is referred to as the shoreline angle. The elevation of the shoreline angle at the time of terrace formation varies with differences in the type of rock being abraded, topography, and exposure to the open sea, but is generally within 5 m of mean sea level (Palmer, 1967).

Marine terraces are used world wide as indicators of coastal deformation and former sea levels (Bloom et al., 1974; Chappell, 1974; Dodge et al., 1983; Muhs, 1983; Muhs, 1985; Lajoie, 1986; Kelsey, 1990; McInelly and Kelsey, 1990; among others). To establish the deformational history of a coastline one needs to determine the elevation of a terrace and the age of the terrace. By comparing the age of the
Figure 5. Conceptualized cross section through a marine terrace on the northern Oregon coast (after Kerns, 1977).

Figure 6. Sea level curve derived from uplifted coral reefs on the Huon Peninsula, New Guinea (after Chappell and Shackleton, 1986).
terrace with a world-wide sea level curve (Figure 6) the elevation at which the terrace formed can be established. It is then a mathematical exercise to determine the amount and rate of deformation that has occurred since terrace formation. For instance, if a 10,000 year old terrace is presently at an elevation of 90 m and was formed at an elevation of -10 m below present sea level, then the terrace has been uplifted 100 m in 10,000 years or 10 m/1000 yrs. If a dated terrace can be correlated along a section of coastline then the rates, styles, and variations of coastal deformation can be defined. By determining the ages of other terraces and assuming a constant uplift rate, it is also possible to determine the position of sea level at the time of terrace formation. For example, if a second terrace is found to be 5,000 years old then the terrace should have been uplifted some 50 m (at 10 m/1000 yrs). If the terrace is presently at an elevation of 30 m this would indicate that sea level 5,000 years ago was at an elevation of -20 m below present sea level. The use of terraces as indicators of paleo-sea levels has been performed in New Guinea (Bloom et al., 1974), Haiti (Dodge et al., 1983), and California (Muhs, 1985), to name a few, and the results are found to be somewhat compatible between locations and with sea level curves derived from oxygen isotopes.
PREVIOUS WORK

Past and recent research on marine terraces in Oregon has generally centered on the prominent terraces in southern Oregon (Diller, 1903; Griggs, 1945; Adams, 1984; McInelly and Kelsey, 1990; Kelsey, 1990, Muhs et al., 1990). Early studies in southern Oregon revolved around the economic potential of black sand deposits in the area. Griggs (1945) named the three youngest terraces at Cape Arago, in ascending order, the Whiskey Run, Pioneer, and Seven Devils terraces. The Whiskey Run terrace has been fairly well dated and is correlated with the 80 thousand year old (ka) high stand of the sea while the Pioneer terrace is believed to represent the 105 ka high stand of the sea (Muhs et al., 1990). These ages and names are followed in this thesis. Recent papers by Adams (1984), McInelly and Kelsey (1990), Kelsey (1990), and Muhs et al. (1990), have focused on the rates, styles and mechanisms of tectonic deformation of terraces in southern Oregon.

In comparison, research on marine terraces of the northern Oregon coast is generally lacking, especially in reference to their tectonic significance. This is probably because of their lack of prominence, due to a low uplift rate when compared to terraces in southern Oregon. In an early geologic mapping project of the Nestucca Bay quadrangle, Snavely (1948) found estuarine terrace deposits...
just north of Cape Kiwanda and correlated them with the Coquille Formation of the southern Oregon coast which was described by Baldwin (1945). Palmer (1967), in a regional study of terraces on the west coast of the United States, noted the presence of marine terraces on the northern Oregon coast. In particular he pointed out a terrace of unknown age at around 400 feet in elevation in the Tillamook area.

Geologic maps which show the extent of the lowest marine terrace along sections of the northern Oregon coast were produced in papers by Mangum (1967), and Lund (1972, 1974), and in the Master's theses of Neel (1976), Frye (1976), and Parker (1991). The most comprehensive map showing the lowest terrace was included in an environmental geology report on coastal Clatsop and Tillamook Counties by Schlicker et al. (1972). These authors also remarked on the fine-grained nature of the terrace sediments and the susceptibility of terrace material to slumping and landsliding.

A stratigraphic and petrologic study of river and coastal terraces in the Tillamook Bay area was performed by Frye (1976). He found the coastal terraces to be predominantly composed of fine sediments probably deposited in a bay or estuary. He also discussed the presence of peat layers, some containing tree stumps, which he speculated were produced by inundation and burial due to rapid sedimentation. Frye (1976) also obtained a radiocarbon date
on a log from the upper part of the Cape Meares Village terrace (just north of Cape Meares). The log was reported to be radiocarbon dead (>40 ka).

Tectonic studies including the terraces of the northern Oregon coast were not published until the late 1980's. Even these studies were generally of a broad nature and did not center wholly on terraces in northern Oregon. West and McCrumb (1988) using limited data from Kennedy (1978) and Heusser (1972) presumed that the lowest terrace along the Washington and Oregon coast (except at Cape Blanco) was the 80 ka Whiskey Run terrace (name given to low terrace in southern Oregon by Griggs, 1945). Using this date West and McCrumb (1988) calculated uplift rates for Washington and Oregon (generally 0.2-0.6 mm/yr) and concluded that the rates are significantly different from other seismically active subduction zones (>0.5 mm/yr and generally >1 mm/yr). This and the fact that there are no uplifted Holocene wave-cut platforms led these authors to speculate that the Juan de Fuca plate is subducting aseismically and might not be generating large earthquakes, at least not during the Holocene.

Peterson et al. (1988), in a neotectonic field trip guide of Netarts Bay, discussed evidence for coastal subsidence within terrace sediments on the east side of the bay. At this location, uplifted estuarine deposits contain intervening organic rich layers which have gradual contacts
with underlying mud and abrupt contacts with overlying mud. This stratigraphy may be created by cycles of tectonic stress accumulation causing uplift followed by rapid strain release causing subsidence. Peterson and Darienzo (1989) also noted the presence of these organic rich layers in Pleistocene terrace sediments from the central Oregon coast up through Washington.
METHODS OF INVESTIGATION

Field work for this study was conducted between the summer of 1990 and the winter of 1992. Mapping of terraces was performed primarily during the first field season with additional information compiled later from maps by Schlicker et al. (1972), Frye (1976), Neel (1976), and U.S. Army Corps of Engineers aerial photos. Terraces were mapped on seven U. S. Geological Survey 7.5 minute topographic quadrangles (Tillamook Head, Arch Cape, Nehalem, Garibaldi, Netarts, Sand Lake, and Nestucca Bay). The terraces were mapped by first walking out beaches and headlands to find outcrops of the terraces and then determining the extent of the terrace from these outcrop locations. Many factors such as heavy vegetation cover, beach or dune sand cover, recent colluvium cover, landsliding, and man made constructions (rip rap, houses, etc.), make it difficult to determine the extent of the terraces in many cases. The landward edges of the terraces were generally mapped where there was an apparent slope break from the fairly flat terrace surface to the steep hills of the surrounding Tertiary bedrock. If no slope break was obvious, a best guess was made based on the available outcrops.
Stratigraphic sections of terrace sediments were measured with a cloth tape measure, and a hoe with a cut off handle was used to clear the weathered surfaces of the sediments. Sections were measured at all outcrops where a lack of cover permitted access. Several locations such as Cannon Beach, Rockaway Beach, Garibaldi, and Tierra Del Mar, had very limited outcrops and no sections were measured. Although an attempt was made to measure sections at representative sites, stratigraphy often varied widely along a single terrace exposure.

Terrace sediments were described based on seven general categories developed for this thesis: gravel, pebbly sand/mud, sand, mud, rooted sand/mud, peaty sand/mud, and peat. A peat layer is a lignitic, almost woody appearing horizon, with little other sediment and is difficult to cut through with a hoe. A peaty sand/mud is a highly organic rich (black) sand or usually a mud which is easily cut through with a hoe. The rest of this text will not distinguish between peat and peaty sand/mud (except in figures showing stratigraphic sections) unless the distinction is deemed necessary.

Three holes were drilled through terrace sediments at Netarts Bay (Hanson site - UTM 5029775 N, 426905 E; Fish site - UTM 5027345 N, 4027107 E; Niflis site - UTM 5027279 N, 426893 E) by the Oregon Department of Transportation (ODOT) to obtain complete stratigraphic sections of the
sediments. Drilling was conducted with a hollow-stem auger with a core catcher which provided continuous cores. Cores were collected in five foot sections and taken to the lab for description.

Diatoms were examined from mud and peat layers in terrace sediments to interpret paleotidal levels based on relative salinity tolerance of diatom species. To obtain diatom specimens a small portion of a mud or peat sample (30-50 cc) was put into a beaker with water and stirred up until the sample had disaggregated. The sample was then run through the 62 micron sieve to remove sand and larger particles. The silt/clay fraction was allowed to settle for two hours, the supernate was poured off, and the remaining mixture was allowed to settle for another two hours. An eye dropper was then used to collect a sample which was put on a slide, diluted with distilled water, and dried on a hot plate for later microscope inspection.

Six soil profiles were described in the field following the guidelines of Soil Taxonomy (Soil Survey Staff, 1975) in order to correlate the lowest terrace surface along the northern Oregon coast. Texture, structure, and wet consistency of the soils were described in the field, and colors were described in the lab using Munsell's color book (Munsell, 1990). Soil pH was recorded in the lab using the 1:1 distilled water method (Soil Survey Staff, 1972) and a
Whatman model 41100 pH meter with a Whatman general purpose silver series electrode.

A quantitative index of soil development, developed by Harden (1982), was used for correlating the terrace soils. This process involved comparing the properties of the C horizon with the B horizon by assigning arbitrary numbers to changes in soil properties (field texture, structure, wet consistence, Munsell color, and pH) between the two horizons (if a soil had two B horizons, the more dominant of the two was used for the comparison). If the soils have the same relative development then the sum of the assigned numbers for each site should be nearly the same (see Birkeland et al., 1991, p. 7-10 for equations used to calculate PDI).

Elevations of terrace surfaces were obtained with an altimeter. All elevation points were tied into sea level. The altimeter, although rated to be accurate to within a meter and a half, is considered to be good to within three meters in this study. The altimeter was checked at several locations of known elevation (after being set at sea level) and was found to be accurate within this range.

When taking elevations of terraces it is preferable to take the reading at the paleoshoreline angle (figure 5) (Palmer, 1967; Bradley and Griggs, 1976). Because of a thick marine sediment cover on top of the wave-cut platforms and a low uplift rate (see results and discussion) of the northern Oregon coast, there are few exposed paleoshoreline
angles of the lowest terrace in the study area. Thus, elevations were taken on the top of the marine sediments as near as possible to the back edge of the terrace (<200 m from the backedge) without incorporating more recent alluvial and colluvial sediments into the measurement. This method of measuring elevations is not highly accurate (Palmer, 1967), but under the circumstances it yields the best available picture of terrace elevation and corresponding regional coastal deformation.

Fifteen stratigraphic sections were measured along a north-south trending 800 m long outcrop at Netarts Bay to identify possible dip angles that could reflect local deformation features. One of these stratigraphic sections (site #6) was later thrown out when it was determined to be part of a slump. The location for this test was chosen because it had a long continuous outcrop, easily interpreted stratigraphy, and because the site lies just onshore of recently mapped offshore deformation structures (Goldfinger et al., 1992). The task was accomplished by tracing a single well developed peat layer (target peat layer) along the outcrop and measuring repeated sections at points that were tied into sea level. In many cases the target peat layer could be physically traced from one measuring point to the next. In several cases the peat layer was covered by slumps or vegetation. In this case the target peat layer was correlated across covered zones by similarities in
stratigraphy and/or by the presence of tree stumps which were present in only one peat layer at all locations in the Netarts shoreline.

A horizontal datum was created along the outcrop by going out to the outcrop at high tide and using a tape measure to measure 1 m above water level (sea level). The elevation point was then marked and the process was quickly repeated at the next site so as not to allow too much variation in sea level. This technique is sufficiently accurate (± 0.5 m) for this study and eliminated the need for difficult surveying around an irregular soft bottomed shoreline. Stratigraphic sections were measured later and the position of the elevation marker and the target peat layer within the section was noted. Thus, the level of the marker in each stratigraphic section should be at the same elevation and the deformation of the target peat horizon can be established relative to the tidal level markers.
RESULTS

A map displaying the locations of marine terraces on the northern Oregon coast is shown in Plate 1. The lowest and presumably the youngest terrace is the most extensive, with higher terraces found in far more restricted locations along the northern Oregon coast. Many of the less obvious upper terraces were probably not mapped due to their overall poor preservation and lack of exposure. This thesis will deal primarily with the lowest terrace with only brief mention given to higher terraces.

The lowest terrace surface ranges in elevation between $11 \pm 3$ m and $20 \pm 3$ m above MSL and is typically exposed directly above the modern beach. Individual terrace segments extend along the coast for distances of 0.1 to 10 km and extend inland anywhere from 20 to 700 m (Plate 1). The terraces are usually cut into relatively soft Tertiary marine sediments and terrace segments are separated by resistant headlands composed mainly of basalts. The lowest terrace has apparently been largely eroded away with only relatively small remnants of a once much larger terrace remaining.

Exposures of terrace sediments consist predominantly of mud, sand, peat, and sometimes gravel when in close
proximity to headlands. Stratigraphy ranges from simple alternating layers of mud and peat to extremely complex assemblages of peat, mud, sand, and gravel of various origins. Peat horizons sometimes contain sticks, twigs, or in many places tree stumps in growth position. Many exposures of terrace sediments contain abundant fragments of wood and other organic material, and in several cases pine cones can be found. The stumps and other woody material in the terrace sediments are well preserved considering their age (minimum age of 40 ka). For example, the wood contains original organic structures showing little evidence of internal decomposition.

DESCRIPTIONS OF INDIVIDUAL TERRACE SEGMENTS

The following sections will describe the location, stratigraphy and general features of individual terrace segments. Names given to terraces (i.e., Indian Beach terrace) do not imply a formal name or an age of formation and are merely used for location purposes. Locations of terrace segments can be seen on Plate 1. The locations of all important points are given in Universal Transverse Mercator (UTM) coordinates. All stratigraphic sections were measured in the present day sea cliff and therefore only the north coordinate was used to give approximate location. The order of presentation of the data goes from north to south.
Indian Beach Terrace Segment

The lowest terrace at Indian Beach is located in a small recess just south of Tillamook Head. The top of the terrace is presently being used for a parking lot for access to Indian Beach in Ecola State Park. The terrace is 0.2 km long and extends inland for 0.12 km. The stratigraphic section was measured directly west of the parking lot at UTM 5086690-N. Terrace sediments have a simple stratigraphy of mud and peat with occasional gravel (Figure 7). Indian Beach contains the greatest number of peat horizons within a single outcrop in the study area, with seven thick, well-developed peats within the section (Figure 8). Several of the peat horizons contain in situ tree stumps. The peats are separated by laminated gray mud and sometimes by gravel which was derived from the nearby cliffs of Tillamook Head.

Cannon Beach/Tolovana Park Terrace Segment

The Cannon Beach/Tolovana Park terrace lies beneath the towns of Cannon Beach and Tolovana Park with a short break in the Haystack Rock area, and extends down to Silver Point. The terrace may extend around Silver Point but extensive landslides in this area make it impossible to identify terrace features. The Cannon Beach portion is 1.5 km long and 0.8 km wide while the Tolovana Park portion is 2.26 km long and extends 0.3 km inland. Terrace sediments are not exposed along the beach (except for a few short sections)
Figure 7. Stratigraphic sections form the Indian Beach, Arcadia Beach, and Hug Point terrace segments.
Figure 8. Indian Beach terrace containing alternating layers of gray mud and black peat.
due to rip rapping, cement walls, and beach and dune sand. A single exposure of barren gray mud is located just off the middle of three exits to Cannon Beach from Highway 101. Another small exposure of laminated mud and two buried peat horizons is located at beach level just north of Silver Point. No stratigraphic sections were measured on the Cannon Beach terrace because of the lack of adequate outcrops.

Arcadia Beach Terrace Segment

The Arcadia Beach terrace begins at Humbug Point on the north and extends for 1 km down Arcadia Beach and 0.17 km inland. The best exposures are located just south of Arcadia Beach State Wayside which is where the stratigraphic section was measured (UTM 5077170-N). The stratigraphy is relatively simple consisting mostly of mud and peats with overlying sand deposits (Figure 7). Peat development is not as good as at Indian Beach, but there is a good record of peaty mud with two lower relatively thick peats. The lowest peat is actually buried by beach sands but can usually be found by digging out the sand. This peat layer was first revealed by occasional tree stumps contained within the peat horizon which stick up above the sand during winter periods of beach erosion.
Hug Point Terrace Segment

The Hug Point terrace is an aerially limited terrace segment located within Hug Point State Park. The terrace is 0.2 km long and 0.12 km wide and can be seen in the sea cliff just south of the Hug Point State Park parking lot, although much of the outcrop is covered by vegetation. The vegetation effectively splits the exposed section (UTM 5075130-N) into a lower part containing mud and two well developed peats, a middle part that was covered by brush, and an upper part consisting of mud, sand, gravel, peaty sands and an organic detritus layer (Figure 7). The southern most exposure of the terrace segment contains the two lowermost peats with the upper peat buried by a landslide containing large boulders (about 2 m in diameter).

Arch Cape Terrace Segment

The Arch Cape terrace segment underlies the town and residential neighborhoods of Arch Cape. The terrace is approximately 2 km long and has a maximum width of 0.36 km. Exposures of terrace sediments are largely covered by vegetation, sand, cement walls, and rip rap. However, a slump in the middle part of the segment (UTM 5073830-N) provides an almost complete section of the terrace sediments. This section contains numerous buried peats and an organic detritus layer interbedded with laminated mud, sand, and gravel (Figure 9).
Figure 9. Stratigraphic sections from the Arch Cape, Cove Beach, and Short Sand Beach terrace segments.
Cove Beach Terrace Segment

The terrace segment at Cove Beach (or Falcon Cove) extends for 1.6 km, from the southern part of Arch Cape down to the northern end of Cape Falcon, and has a maximum width of 0.2 km. The northern half of this segment is almost entirely covered by vegetation and logs washed in by the ocean. The southern half contains good exposures (UTM 5070330-N) in the sea cliff due to many recent slumps produced through undercutting by the sea (Figure 10). The upper two-thirds of these exposures consists predominantly of gravel probably derived from the steep hills and headlands of the area (Figure 9). The bottom third consists of sand, mud, and two peat horizons. The peat horizons in this area are very irregular in that they seem to disappear and reappear in a different form down the exposure. In one area they may appear as peat horizons while in another area they may consist of organic rich layers with branches and twigs sticking out, while in other areas they are not present. This attribute is not unique to this locality but seems to be more pronounced than at other sites in the study area. These variations are likely due to facies changes of the same unit.

The Cove Beach terrace segment also contains many features which may indicate liquefaction of sediments. These features include flame structures, contorted bedding, sand
Figure 10. Cove Beach terrace showing the slope retreat which is common to many terrace segments.
volcanoes, and chaotic mud layers that contain wood debris oriented with the long axis vertical (Figure 11).

**Short Sand Beach Terrace Segment**

Short Sand Beach contains a very small terrace segment (0.14 km long and 0.12 km wide) on the southern part of the beach. A single outcrop can be seen right where the trail from Highway 101 meets the beach (UTM 5067570-N). This outcrop consists of a lower section made up of mud, pebbly mud, and two thick peat layers, a middle section containing cobbles and gravel, and a upper section of pebbly mud with occasional cobbles (Figure 9). The thicknesses of the upper units on the stratigraphic section (Figure 9) are approximate since the outcrop is a vertical cliff with poor access.

**Rockaway/Twin Rocks Terrace Segment**

Outcrops in this terrace segment are very scarce even though the segment is 7 km long and 0.6 km wide. A couple of small sections of mud can be seen in roadcuts on Highway 101 at the southern end of the terrace segment and some very tiny outcrops can be seen on Highway 101 by Manhattan Beach High School. No measured sections were taken at these outcrops.
Figure 11. Liquefaction features from the Cove Beach terrace segment. Top: contorted bedding just to the right of the quarter; Bottom: sand volcano, notice pebble train below and also to the left of the quarter and the disrupted whitish bed above and to the left of the quarter.
Garibaldi Terrace Segment

This terrace segment underlies the town of Garibaldi and is approximately 2 km long and 0.5 km wide. Only one outcrop of the terrace was found, located in a roadcut on Highway 101 on the north side of town. The outcrop consists predominantly of pebbly mud, but no stratigraphic section was measured because the exposure was so small. Irregular topography over most of this area is the result of landsliding (Schlicker et al., 1972) and makes mapping of the back edge of the terrace difficult to interpret.

North Cape Meares Terrace Segment

This terrace segment is about 0.8 km long and 0.5 km wide, and underlies the community of Cape Meares Village which is located just north of Cape Meares. Much of Cape Meares Village actually sits on top of a recent and still active landslide which has largely overridden the terrace. However, terrace sediments can still be seen in the present day sea cliff underlying the landslide (Figure 12). The terrace sediments at the site of the stratigraphic section (UTM 5038290-N) consist predominantly of mud with some sand and peat (Figure 13). Once again the bottom part of the terrace has two fairly well developed peat horizons. Many of the mud layers in this segment contain abundant wood debris that is oriented with the long axis at different angles indicating possible liquefaction of the mud. The
Figure 12. North Cape Meares terrace. The bottom one-third of the photo is terrace sediments and the top two-thirds is an active landslide.
Figure 13. Stratigraphic section from the north Cape Meares terrace segment.
terrace segment at North Cape Meares actually contains a large amount of gravel (except at the location of the measured section) which is once again probably derived from the nearby headland.

South Cape Meares Terrace Segment

The south Cape Meares terrace is located in the sea cliff of Short Beach just south of Cape Meares. This site contains a wave-cut platform at an elevation of 18 ± 3 m which is approximately 0.6 km long and 0.08 km wide. The wave cut platform is overlain by gravel which is unreachable because of the steep cliff. Just north of this site a high wave-cut platform can be seen on which the Cape Meares Lighthouse now stands. This terrace is at an elevation of about 80 m. The same wave-cut platform can also be seen on top of the most easterly sea stack of Three Arch Rocks located a little over 2 km to the south.

Netarts Bay Terrace Segment

The east side of Netarts Bay is the location of the most continuous terrace segment on the northern Oregon coast. The terrace extends from the town of Netarts south to Cape Lookout, a total distance of about 10 km, with only one minor break. The Netarts Bay segment is also the widest terrace segment having a maximum width of about 0.75 km. Several small outcrops of the terrace can be seen in roadcuts on the Three Capes Scenic Highway in Netarts and on
various city and private roads in the northern half of the terrace segment (Figure 14a measured at UTM 5028024-N). The southern half of the terrace segment has several good outcrops located just above the modern bay. The best exposure is between Wee Willies Restaurant (UTM 5027670-N) and the Whiskey Creek Fish Hatchery (UTM 5027110-N) (Figure 15). Here the terrace sediments consist entirely of laminated gray mud with interlayered peat horizons (Figure 14b measured at UTM 5027125-N). One of these peat layers can be fairly easily traced along the whole segment, a distance of about 800 m. About a half km south of the fish hatchery another outcrop of barren mud and peat can be seen (Figure 14c measured at UTM 5026810-N). Further south of this outcrop the sediments become fluvial in nature with several ancient landslides also included.

Drill cores from Netarts Bay (Figure 15) have provided relatively long continuous sections of terrace sediments. Stratigraphic sections of the cores are shown in Figure 16 and detailed descriptions of the sediments are given in the Appendix. The Fish and Niflis sites (UTM 5027345-N, 427110-E and UTM 5027180-N, 426890-E respectively) consisted almost exclusively of mud and buried peat horizons, but neither site reached bedrock. Both of these cores were found to contain sequences of peat overlain by laminated fine sandy mud (>15-20% sand), overlain by mud (<10-15% sand), and finally overlain by either another peat horizon or another
Figure 14. Stratigraphic sections from the Netarts Bay terrace segment (see figure 15 for locations): (a) just north of Wee Willies; (b) just north of the fish hatchery; (c) about one-half km south of the fish hatchery.
Figure 15. Map of Netarts Bay showing the locations of the three drill sites (black dots) plus Wee Willies and the Whiskey Creek Fish Hatchery.
Figure 16. Stratigraphic sections compiled from drill cores at Netarts Bay. The elevations of the tops of the drill cores are from left to right 6.3 m, 19.2 m, and 15 m. Arrows indicate a fining up sequence from a lower intertidal fine sandy mud to an upper intertidal mud.
laminated fine sandy mud. These fining upward sequences (from a fine sandy mud to a mud) are indicated by the arrows on Figure 16. The Hanson drill site (UTM 5029725-N, 426905-E) consisted of mud, sand, and buried peat horizons in the upper part of the core and clean beach sand in the bottom part of the core. Only the very top part of the sand was collected since the core barrel could not catch the loose sand and the core barrel broke off within the top 4 m of the sand. Drilling continued at the Hanson site without core collection until the driller reported hitting something hard at about 18 m below land surface. Several chunks of this hard material stuck to the drill bit and was found to be a weathered siltstone. This likely represents the depth of the wave-cut platform cut into the Tertiary bedrock. All three drill sites were surveyed into sea level and found to be at elevations of: Hanson site = 6.3 m; Niflis site = 19.2 m; Fish site = 15 m. The Hanson site has a low elevation because it was not drilled from the top of the terrace surface.

Just north of Happy Camp (located just north of Netarts) a wave-cut platform cut into a basalt breccia can be seen about 15 ± 3 m above the beach in the sea cliff. The platform is overlain and largely obscured by dune sands. This location has received a lot of attention lately because of a possible thrust fault (Figure 17), located at UTM 5032330-N, which offsets a Quaternary stream wall and
Figure 17. Possible thrust fault (dashed line) just north of Happy Camp. Fault offsets Quaternary basaltic stream gravel and the stream wall, made up of Tertiary basaltic breccia, about one meter. The small blue object in the lower center part of the picture is a camera case.
fluvial gravels about 1 m (R. E. Wells, 1992, personal communication). However, no offset of the wave-cut platform was seen during this study.

**North Cape Lookout Terrace Segment**

This terrace segment is located just north of Cape Lookout within Cape Lookout State Park. Outcrops of the terrace can be seen just west and south of the picnic area at Cape Lookout State Park. The terrace is a small portion of the Netarts Bay terrace segment which is 1.5 km long and 0.5 km wide. This location along with Cove Beach and north Cape Meares have the most complicated stratigraphies of all the terraces observed on the northern Oregon coast. At Cape Lookout, the sediments range from colluvial gravels, to gravels deposited by landslides, to fluvial cut-and-fill sands and gravels, to mud and sands deposited in much quieter environments. The stratigraphic section was measured at a site (UTM 5022930-N) that contained predominantly mud, sand and peat (Figure 18). Two peat horizons appear to dominate throughout the entire outcrop. The peat horizons at two locations along the outcrop contain large in situ tree trunks which are 2-3 m tall with roots that extend laterally for 3-5 m (Figure 19). The southern part of the outcrop contains a section of terrace mud and peat (about 10 m long and 3-4 m high) that appears to be
Figure 18. Stratigraphic sections from the Cape Lookout and Cape Kiwanda terrace segments.
Figure 19. Cape Lookout terrace containing a large in situ tree trunk.
tilted to the north but is actually wholly contained within a landslide.

South Cape Lookout Terrace Segment

Just south of Cape Lookout, within the Boy Scouts' Camp Meriwether, a wave-cut platform cut into basalt can be seen in the sea cliff at an elevation of approximately 15 m. Cobbles and gravels lie on top of the wave-cut platform but could not be reached because of the steep cliff.

Tierra Del Mar Terrace Segment

The Tierra Del Mar segment can be seen in the town of Tierra Del Mar and further north on the southeast shore of Sand Lake. Small outcrops made up of pebbly mud/sand can be seen on the east side of the Three Capes Scenic Highway all through this zone. However, no peat horizons are seen in these outcrops.

Cape Kiwanda Terrace Segment

Just north of Cape Kiwanda several outcrops of terrace sediments can be seen in the sea cliff. These outcrops consist of mud, sand, and buried peat (Figure 18 measured at UTM 5008240-N), with one site containing a peat layer that is 1.5 m thick. Dune sand has overridden and concealed most of this terrace segment.

Terrace deposits can also be seen on top of Cape Kiwanda by walking up the south side to the first
observation point. Just beyond the cable fence lies a pebbly gravel deposit on top of a crude wave-cut platform. About 50 m north of this last site two or possibly three buried peat horizons can be seen in the cliffs, but they are inaccessible because of the steep cliff. Both of these sites are at an elevation of about 18 ± 3 m.

DIATOMS IN TERRACE SEDIMENTS

Fifteen diatom slides from terrace outcrops at Netarts Bay and eight slides from drill cores at Netarts Bay were analyzed for this study in order to determine depositional environments (fresh, brackish, or salt water) of mud and peat layers. Analysis of slides revealed few diatoms and very poor preservation of diatoms that did exist (M. E. Darienzo, 1991, personal communication). A single marine centric diatom (Actinoptychus) was identified from a mud layer at the 735 cm level of the Fish drill site. A similar investigation was performed on sediments from several terrace sites on the northern Oregon coast in 1988 with the same results except for one fresh water diatom identified in a buried peat horizon at Cove Beach (M. E. Darienzo, 1991, personal communication).

AGE AND CORRELATION OF THE LOWEST TERRACE SURFACE

The lowest terrace throughout Oregon and Washington has been correlated by West and McCrumb (1988) to the 80 ka
Whiskey Run terrace of southern Oregon. However, no absolute dating of the terrace in the present study area was performed by these authors. Frye (1976) radiocarbon dated a piece of wood from the north Cape Meares terrace segment and reported it to be radiocarbon dead (>40 ka). A radiocarbon date on a piece of wood from the Hug Point terrace segment was obtained for this study and it also was found to be radiocarbon dead, or >44.9 ka (Beta Analytical #40753, 1990). The piece of wood was taken from the higher of two peats in the lower part of the terrace section (Figure 7). So the lowest terrace in northern Oregon is >40 ka. Its actual date of formation remains unknown. However, based on the relative position of the terrace (i.e. being the lowest terrace in the study area), and on ages of the lowest terrace in southern Oregon and Washington (Muhs et al., 1990 and Heusser, 1972, respectively), the lowest terrace in northern Oregon is tentatively correlated to the 80 ka Whiskey Run terrace.

To accurately date the time of formation of a marine terrace older than 40-45 ka (limits of radiocarbon dating) requires uranium-series dating of fossil corals (Muhs and Szabo, 1982). This a problem on the northern Oregon coast since corals are rare in mid- and high-latitude deposits of the north Pacific (Muhs and Kennedy, 1985). No fossil corals nor any fossil shells were found in terrace deposits during this study. Several trace fossils (burrows) were
seen on occasion. Thus, in order to correlate the lowest terrace surface along the northern Oregon coast it was necessary to employ relative dating techniques using soil development.

Soil profiles and the properties of individual horizons are shown in Table I for the following locations: Cannon Beach (UTM 5082050-N, 425540-E), Arcadia Beach (UTM 5077240-N, 425500-E), Hug Point (UTM 5075180-N, 425380-E), Arch Cape (UTM 5073850-N, 425480-E), Cove Beach (UTM 5070460-N, 424785-E), and Cape Lookout (UTM 5023070-N, 424000-E). The soils examined in the field for this study looked remarkably similar for all six locations, and all of them exhibited similar Inceptisol development (Figure 20). Using a method developed by Harden (1982) and demonstrated by Birkeland et al. (1991) a profile development index (PDI) was calculated for each soil using the properties of rubification, melanization, texture, structure, and pH. An increase in the PDI indicates that a soil is more developed. The PDI's calculated for each soil are: Cannon Beach = 100, Arcadia Beach = 70, Hug Point = 100, Arch Cape = 100, Cove Beach = 90, Cape Lookout = 50. The mean for the PDI's is 85 and the standard deviation is 21. The low PDI for the Cape Lookout soil may be because the soil was formed in loose sand while the other soils were much more silt and clay rich.
## TABLE I

DESCRIPTIONS OF SOILS ON THE LOWEST TERRACE SURFACE

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For texture: cl=clay loam, l=loam, sil=silt loam, scl=sandy clay loam, ls=loamy sand. For structure: mass=massive, w=weak, mod=moderate, s=strong, f=fine, m=medium, c=coarse, sbk=subangular blocky. For wet consistance: ns=nonsticky, ss=slightly sticky, s=sticky.
Figure 20. Soil profile from the Hug Point terrace segment typical of soils on the lowest terrace surface.
A recent reconnaissance study by Scott Burns (personal communication, 1992) has shown the soils of the lowest terrace on the northern Oregon coast to be very similar to the soils of the lowest terrace on the central Oregon coast. The lowest terrace on the central Oregon coast has been correlated to 80 ka Whiskey Run terrace of southern Oregon (Harvey Kelsey, personal communication, 1992). In addition, there is a clear progression in soil development from youngest to oldest terrace on the central Oregon coast (Scott Burns, personal communication, 1992).

ELEVATION AND TECTONIC DEFORMATION OF TERRACES

Figure 21 shows the elevation of the lowest terrace at almost all terrace segments along the northern Oregon coast. As mentioned before these elevations were taken on top of the sediment cap which overlies the buried and unexposed wave-cut platform. These measurements are considered accurate enough for defining regional styles and rates of deformation. A question mark was put next to the north Cape Meares elevation because the terrace is overlain by a large landslide and the only place to take an elevation was at the present day sea cliff. This measurement is probably a little low since the back edge of the terrace could not be reached. No elevation for the Cape Kiwanda terrace segment is shown because of the thick dune sands which cover the top of the terrace. The age of these sand deposits are unknown.
Figure 21. Elevations with error bars of the lowest terrace surface along the northern Oregon coast.
As can be seen from Figure 21 there has been little uplift (11-20 ±3 m above MSL) and very little along-coast variation in uplift of the terrace. This low uplift rate is one of the reasons for the lack of exposure in the present sea cliffs or coastal stream cuts of the wave-cut platform and shoreline angle which are the preferable spots to measure elevations. The small amount of uplift has put the soft terrace deposits in a position were they are actively being eroded away by the present sea level. This is why only small remnants of a once much larger terrace exists today.

The absolute uplift of the terrace depends on which eustatic sea level curve is used to determine the elevation of sea level at the time of terrace formation. A popular sea level curve deduced from uplifted coral reefs on the Huon Peninsula, New Guinea, puts sea level at ~19 ± 5 m below present sea level at 80 ka (Chappell and Shackleton, 1986) (Figure 6). This would mean an absolute uplift of around 30-39 m for the lowest terrace on the northern Oregon coast (assuming an age of 80 ka). That is a net rate of approximately 38-49 cm/1000 yrs.

Figure 22 shows a stratigraphic cross section created with the fourteen stratigraphic sections measured along a single north-south trending outcrop on Netarts Bay. Each stratigraphic section contains an arrow which indicates the location of the tidal marker (see methods of investigation).
Figure 22. Stratigraphic cross section from an outcrop at Netarts Bay between Wee Willies and the Whiskey Creek Fish Hatchery (see figure 15). Solid lines indicate that the target peat layer could be physically traced between locations while dashed lines indicate that the target peat layer was covered by brush or slumps between locations.
By placing all the arrows at zero it is possible to determine the deformation of the target peat layer relative to the tidal marker. The top of the target peat layer is marked by a solid or dashed line. Figure 22 shows little discernable deformation of the peat layer in the northern two-thirds of the outcrop. The middle part of the outcrop may contain vertical offset but stratigraphic sections are too few and far between due to inadequate exposure to make any interpretations. On the southern third of Figure 22 a distinctive synclinal feature is apparent. The synclinal feature can also be recognized in the field. However, the short wavelength (200 m) and small amplitude (1 m) of the synclinal feature probably preclude it from being a major structure of any significance. Furthermore, there is no apparent overall tilt of the peat layer to the north or south from one side of the outcrop to the other.
DISCUSSION

DEPOSITIONAL ENVIRONMENT OF TERRACE SEDIMENTS

The lowest terrace in northern Oregon is rather unusual when compared to descriptions of terraces from other parts of the Cascadia margin. The terraces of southern Oregon usually consist of a wave-cut platform overlain by a gravel basal lag deposit generally overlain by sand and gravel deposits (Kelsey, 1990). This type of stratigraphy is interpreted as having been deposited in open beach and nearshore environments. On the northern Oregon coast the wave-cut platform of the lowest terrace is not generally exposed and terrace sediments consist predominantly of fine sediments (clay, silt, and fine sand). These sediments were not deposited in a high energy beach environment but in something much quieter, such as a bay or estuary. This is in agreement with Frye (1976) who found the lowest terrace in the Tillamook Bay area to contain abundant fine sediment (fine sand to silt) deposited in a quiet environment. A single marine diatom found in a mud layer from the drill core at the Fish site supports but can not independently confirm that the sediments are intertidal in origin. Analogs for deposition of these terrace sediments in back-barrier marine environments are the modern bays now existing
on the northern Oregon coast. Holocene bays and estuaries provide a modern example of all environments which can be seen in the Pleistocene sediments. The best example of this fact can be seen at Netarts Bay where laminated tidal flat mud, organic-rich mud, buried marsh surfaces, sand, landslide debris, and fluvial sediments can all be seen in both the modern bay and in Pleistocene terrace sediments.

The fact that many of the terrace sediments were deposited in bays or estuaries is significant since it implies that a large portion of the northern Oregon coast was protected by barrier islands during this previous marine high stand. The nature and exact extent of the barrier systems are not further addressed in this study. The barrier deposits themselves have been destroyed or redistributed by the Holocene eustatic sea level rise.

Gravel deposits contained within terrace sediments are interpreted to be landslide, colluvial or sometimes fluvial deposits derived from nearby headlands and steep hills surrounding the paleobays. Gravel deposits are abundant in many outcrops because the terrace is eroded nearly back to its backedge where abundant landslide and colluvial deposits occur due to the proximity of the old bay cliffs.

Other significant features of the terrace sediments are the peat horizons interlayered with the bay sediments. In many cases tree stumps in growth position can be seen within the peat horizons. The peat horizons are interpreted to be
buried marsh and/or lowland forest surfaces. A close inspection of the peat horizons generally show them to have gradual contacts with underlying sediments and sharp contacts with overlying sediments (Figure 23). This indicates that the peat horizons formed gradually and were buried quickly. A process which could create such stratigraphy in the paleobays is coastal uplift and sudden subsidence due to an active subduction zone.

When a subducting plate becomes coupled to the overriding continental plate, the leading edge of the continental plate is dragged downward while some area inland of a zero isobase is uplifted (Figure 24) (Ando and Balazs, 1979). If the northern Oregon coastline was in the area of interseismic uplift, the paleobays would be episodically uplifted relative to sea level, causing the margins of the bays to rise above sea level and allowing for the gradual formation of marsh and forest surfaces. When an interplate dislocation event occurs, the leading edge of the continent is uplifted and the inland area is downdropped (Figure 24). This would cause an abrupt subsidence of the marsh and forest surfaces below sea level and the sudden burial by bay sediments. This process would then repeat creating a sequence of "stacked peats" like the ones seen in the terrace sediments. The peat horizons in the Pleistocene sediments are considered to be directly analogous to the buried marsh surfaces seen in many Holocene bays along the
Figure 21. Peat layer from Netarts Bay showing gradual lower contact and abrupt upper contact with bay mud.
Figure 24. Diagrammatic sketch of continental deformation during interseismic (top) and coseismic (bottom) periods (after Ando and Balazs, 1979).
northern Cascadia margin (Atwater, 1987; Darienzo and Peterson, 1990). Tsunami sand layers are occasionally seen overlying peat layers in the Holocene deposits (Darienzo and Peterson, 1990). A possible tsunami layer was seen when measuring the stratigraphic section at the north Cape Lookout terrace segment (the sand layer is not shown in Figure 18 because it was too thin). However, no other obvious sand layers were seen above peats in the Pleistocene deposits. This may be because the tsunami layers are silty sediments which are difficult to distinguish from overlying mud, or because the layers have been weathered. Or, it may be that tsunamis did not reach any of the marshes exposed in the present outcrops.

Another indication that the stacked peat sequences have a tectonic origin is the spacing between peat layers. Using the Fish and Niflis drill cores as examples it is found that the spacing between peat layers varies from 5 to 139 cm and averages 48 cm. For a marsh or forest horizon to be buried by lower intertidal sediments there has to be at least 1 to 2 m (Darienzo, 1991) of coastal subsidence or rise in sea level. The same is true for lower intertidal sediments that grade up into marsh or forest surfaces. In this case there must be 1 to 2 m of coastal uplift or drop in sea level. Because there is only an average of 48 cm of sediments between peats, sedimentation can only account for part of the apparent elevation changes (Figure 25). The additional
Figure 25. For a marsh surface to be buried by intertidal sediments there needs to be at least 1 to 2 m of coastal subsidence or rise in sea level (or vice versa). However, on the average only 48 cm of sediments are seen between peat layers. The missing parts of the section are due to tectonic movements of coast.
elevation changes must be due to uplift or subsidence of the coast caused by tectonic forces.

The maximum number of peats is seen in the Fish drill core which has 18 peats over a 17 m interval. Of these 18 peats 11 of them appear to be good well developed horizons. If it took 2000-5000 years for these sediments to be deposited (crude estimate from sea level curve of Chapell and Shackleton, 1986) this would indicate an earthquake recurrence interval of 180-450 years. This estimate is extremely crude but bears some resemblance to the 450 year recurrence interval now being suggested from Holocene data.

In many of the terrace outcrops the peat horizons represent very complicated features. In some cases the horizon will fade in and out and sometimes it will disappear all together. In some places peats will turn into peaty muds and vice versa and in several cases solid layers of detrital sticks and twigs can be seen. These features were very puzzling for a long time until it was noticed that all of these features could be explained by examining the modern bays. Figure 26 shows several different environments within Netarts Bay. If the bay was suddenly downdropped, the margins would become covered with sea water and buried by bay sediments. If, hypothetically, the bay was then suddenly uplifted so it could be looked at, the expression of the subsidence event would vary depending on which environment was buried. For instance, a buried forest would
Figure 26. Different environments around Netarts Bay including lowland forest, salt marsh, and tidal flat.
appear as a peat layer with tree trunks, a high well
established marsh would appear as a peat, while a low young
marsh might appear as a peaty mud. A buried layer of sticks
and twigs would indicate that one was seeing a back bay
margin where branches and wood is often seen collecting in
the modern bays. If a peat layer suddenly disappeared along
an outcrop, it might indicate a change from a buried marsh
to a buried tidal flat while if a peat turned into a peaty
mud it might indicate a change from a buried high marsh to a
buried low marsh. Thus, what form of peat is seen in the
Pleistocene outcrops is dependent on the environment buried
and also on the present exposure. For instance, if a peaty
mud is presently exposed in an outcrop it might appear as a
peat layer if the exposure is eroded some distance further
shoreward.

Taking this idea one step further, if a tidal flat was
subsided and submerged further below sea level would there
be any evidence of the subsidence event? The answer to this
question might have been found in the drill cores recovered
from Netarts Bay. In many cases the drill cores contained a
sequence of peat, overlain by fine sandy mud (>15-20% sand)
grading into a barren mud (<10-15% sand), and finally
grading into another peat layer (fining up sequences shown
in Figure 16). The sediments indicate that (1) the lower
peat layer was subsided to a low intertidal level; (2) the
peat layer was buried by fine sandy mud; (3) the tidal flat
was slowly uplifted to a high intertidal region where the barren bay mud was deposited; and finally (4) the mud flat was uplifted to the point where another marsh was formed. Similar changes in grain size from lower intertidal sandy mud to upper intertidal mud have been reported from other bays on the Cascadia margin (Clifton et al., 1980; Peterson et al., 1982). In several of the Netarts core sections the upper peat layer was missing in the sequence described above and a fine sandy mud graded into a mud and then was overlain by another fine sandy mud. This sequence is thought to indicate that the intertidal mud flats of the paleobay underwent alternating cycles of uplift and subsidence without the uplift being sufficient to allow for the formation of an established wetland at the drill sites.

Other aspects of terrace sediments which may indicate seismic shaking are liquefaction features. Large scale liquefaction features have been found in terrace sediments in the central Cascadia margin (Peterson et al., 1991b). Additional studies are needed to better understand the origin and significance of these liquefaction features.

No large scale liquefaction was seen in northern Oregon terrace sediments, but, many small scale liquefaction features (0.5-1 m) were noticed at the Cove Beach, North Cape Meares, Netarts, and Cape Lookout terrace segments. These generally consisted of sand dikes, flame structures, sand volcanoes, and contorted bedding. Another interesting
and somewhat unusual feature was the presence of chaotic beds of mud mixed with organic material. These chaotic beds consist predominantly of mud with many small (1-3 cm) pieces of wood and other organic materials. Significantly, the wood fragments in many cases were standing with the long axis vertical or at odd angles, instead of horizontal as they were originally laid down. In addition, wood trains (somewhat continuous layers of wood debris) were seen to be deformed and contorted. These features indicate deformation of fluidized muddy or sandy material.

AGE OF THE LOWEST TERRACE SURFACE

As mentioned above the lowest terrace surface along the Washington and Oregon coast (except at Cape Blanco) has been tentatively correlated to the 80 ka Whiskey Run terrace by West and McCrumb (1988) even though no absolute dating has been performed except in southern Oregon. Two radiocarbon dates from the northern Oregon coast (this study and Frye, 1976) show the lowest terrace to be older than 40 ka. Since the terrace is too old for radiocarbon dating and no fossils were found for possible uranium dating, the absolute date of the terrace remains unknown. However, based on the radiocarbon dates from northern Oregon, on the 80 ka age of the lowest terrace in southern Oregon (Muhs et al., 1990), and an estimated age of approximately 80 ka for the lowest terrace at Kalaloch, Washington (Huesser, 1972), an age of
80 ka for the lowest terrace in northern Oregon is not unreasonable. Other possibilities are that the terrace was formed during either the 60 or 105 ka high stands of the sea. The age of the terrace becomes important when determining the amount and rate of coastal deformation.

**CORRELATION OF THE LOWEST TERRACE SURFACE**

Before using a terrace to determine along coast differences in deformation it must be shown that the terrace surface being used is correlated along the coast. If the terrace is continuous along the coast, this a relatively simple matter. However, along the northern Oregon coast the terrace is found in discrete segments and therefore the terrace must be correlated using other techniques. One possibility is dating the terrace at several locations, a process that has proven difficult on the northern Oregon coast. Another possibility, used in this study, is using soil development on the terrace surface as a relative dating technique.

The soils examined on the lowest terrace surface in this study are found to be similar in their development based on their PDI, and all exhibited similar Inceptisol development. The similarities in development from site to site and the closeness of calculated PDI's indicate that the lowest terrace surface is of the same relative age along the northern Oregon coast. Furthermore, the similarities in
soil development from the lowest terrace on the northern Oregon coast and the 80 ka terrace on the central Oregon coast indicates that the terraces are of the same relative age.

TECTONIC DEFORMATION OF TERRACES

The lowest terrace in northern Oregon ranges in elevation from 11-20 ± 3 m above sea level and averages about 15 m. If the lowest terrace is 80 ka, this yields an uplift rate of 38-49 cm/1000 yrs. This rate is in reasonably close agreement with the 30-35 cm/1000 yrs. uplift rate reported by West and McCrumb (1988) for this area.

Both the amount and rate of deformation are rather low when compared to terraces in southern Oregon and in parts of northern Washington. The monotonous elevation of the terrace along the coast is also rather remarkable. Along coast variation in uplift is so small (Figure 21) in northern Oregon that the elevation of the wave-cut platform for the lowest terrace, when cut into relatively soft Tertiary marine sediments, does not even vary enough to become exposed above the modern beach. In southern Oregon the Whiskey Run terrace (80 ka) ranges in elevation from below sea level to 53 m above sea level (McInelly and Kelsey, 1990; Kelsey, 1990). The terrace is deformed by numerous folds and reverse faults. In Washington there is
less control but the lowest terrace does seem to vary quite a bit in elevation along the coast (Figure 27), especially in northern Washington.

The reason for the disparities in the amounts of deformation between the northern Oregon coast and elsewhere may be numerous, but one reason may have to do with tectonic setting. South of the study area the trench becomes progressively closer to the coastline (Figure 1), reaching a minimum at Cape Blanco of about 60 km. Reconnaissance surveys show that terraces become progressively more deformed with increasing distance south from the northern Oregon study area. The proximity of the trench and subsequent shallow depth of the subducting slab in southern Oregon might serve to place the coastline close enough to the accretionary prism for it to experience compressional deformation and resulting terrace warping. Off Washington the curvature of the margin and subsequent curvature of the trench (Figure 1) is thought to cause an arch (see Figure 4 of Crosson and Owens, 1987) in the subducting plate, resulting in local widening of the accretionary prism and the uplift of the Olympic Mountains. This arch has probably also significantly affected the amount of deformation of marine terraces along the adjacent Washington coast. Meanwhile, in northern Oregon the trench is 120 km from the coastline and it runs parallel to the coast. This part of
Figure 27. Elevation picks on the lowest marine terrace in Washington and extreme northern Oregon. Elevations estimated from aerial photos and topographic quadrangles for sites spaced at about 0.5 km intervals (from Peterson et al, 1991a).
the Cascadia margin might be expected to show the least deformation of coastal terraces.

An interesting aspect about the amount of uplift of the lowest terrace is that the terrace is now being reoccupied by the present high sea level stand. This is apparently not an uncommon feature for marine terraces. Kelsey (1990) found a single wave-cut surface at Cape Blanco which was at least partially occupied by three different high stands of eustatic sea level. If the present undercutting of the lowest terrace in northern Oregon continues for much longer the upper most terrace deposits will probably cease to exist. Additionally, the low uplift rate of the northern Oregon coast and the recent eustatic rise of the sea to its highest level since the 120 ka high sea stand have probably caused the erosion and destruction of any terraces which might have formed after and thus lower then the 80 ka terrace.

Several wave-cut platforms along the northern Oregon coast (Short Beach, Happy Camp, South Cape Lookout, and Cape Kiwanda) are found to be at an elevation of about 15 ± 3 m to 18 ± 3 m. These wave-cut platforms are always found in hard, generally basaltic rocks. These wave-cut platforms may represent a terrace older than 80 ka, but there coincidental elevation match with what has so far been called the 80 ka terrace may indicate that they are of the same age. This is possible because wave-cut platforms are cut deeply into soft
rocks while staying shallow in hard rocks. Thus, wave-cut platforms cut into relatively soft Tertiary marine sediments on the northern Oregon coast may be deep and unexposed (i.e. covered with thick marine sediments) while platforms carved into hard resistant headlands may be higher and exposed in the present day sea cliffs.

The monotony of regional deformation along the northern Oregon coast (Figure 21) is also supported by the lack of local deformational features (Figure 22). Figure 22 indicates that there is no overall tilting of terrace sediments along an 800 meter outcrop at Netarts Bay. This result is in contrast to offshore mapping by Goldfinger et al. (1992) which indicates that several recently active folds and faults come onshore at or near this location (Figure 3). If this is so, terrace sediments should show local tilting/warping, but they do not show it at this location. In fact, terrace sediments at all locations within the study area are flat lying and show no obvious deformation (besides regional uplift) indicating folding or faulting. This conclusion would also indicate that some vertically deforming structures mapped onshore in Tertiary rocks (Plate 1) have been largely inactive in the late Quaternary. It is possible that there are active structures in the gaps between terrace segments but these structures would probably impart some tilt to terrace sediments at some
location, a feature which has not been seen during this study.

Although no obvious folding was seen in terrace sediments during this study, dip-slip faulting may be much more difficult to identify. It is unclear whether a fault cutting the lowest terrace could be identified unless it was directly seen cutting terrace sediments in outcrop or had imparted a distinct elevation difference in the terrace. Neither of these features were seen during this study. However, it seems likely that if significant vertical offsets have occurred on any faults, that tilting of terrace sediments and possibly exposure of the wave-cut platform would occur. This does not rule out the possibility of small offsets on widely spaced faults that coincidently do not intersect preserved terrace segments.

A potentially active fault has been mapped by Ray Wells (USGS, Menlo Park) in the sea cliff just north of Happy Camp (Figure 17). At this location, Quaternary basaltic stream gravels are thought to be offset about 1 m by a thrust fault (R.E. Wells, 1992, personal communication). However, evidence for offset of a wave-cut platform higher in the sea cliff was not seen during this study, although 1 m of offset on the platform might be difficult to detect.

North-south geodetic surveys in Oregon have shown down to the south tilt from Tillamook to Astoria (Vincent et al., 1989; Mitchell, C., Weldon II, R., Vincent, P., and Pittock,
H., personal communication, handout for fall 1991 AGU meeting). The data compiled in this study for terrace deformation does not agree with the geodetic data. The lowest terrace does not show a down to the south tilt in the study area but rather a constant uplift rate all along the north coast. However, a comparison of terrace deformation on the northern Oregon coast with geodetic data is complicated by the time scales of the two methods. Terraces are used to determine long term coastal deformation (thousands to millions of years) while geodetic data gives a "snap shot" of recent coastal deformation (up to several decades). It is likely that geodetic data is recording short term interseismic elastic deformation while the terraces are showing long term inelastic deformation.
CONCLUSIONS AND FUTURE STUDIES

The lowest marine terrace between Tillamook Head and Cape Kiwanda on the northern Oregon coast is a rather unusual feature which provides several insights into the tectonic and seismic history of the central Cascadia margin. The terrace contains an abundance of fine sediments (clay, silt, and sand) which were deposited in bays comparable to bays which now exist on the northern Oregon coast. The Holocene bays thus provide a modern analog which can be used to interpret the Pleistocene terrace deposits. Almost all of the terrace outcrops contain marsh or lowland forest surfaces which were buried by bay sediments. These features are interpreted to reflect episodic abrupt coastal subsidence events. Such occurrences are likely caused by megathrust dislocation events on the interface between the Juan de Fuca and North American plates. Episodes of subsidence are also indicated by changes in sediment grain size as seen in drill cores from Netarts Bay. Liquefaction features may also indicate seismic shaking events but their origin and formation is poorly understood at this time.

Soil development has indicated that the lowest terrace surface mapped in northern Oregon is of the same relative age. This terrace is tentatively correlated to the 80 ka
Whiskey Run terrace of southern Oregon. If this correlation is correct the uplift rate of the northern Oregon coast is 38-49 cm/1000 years. This rate is apparently relatively constant along the entire northern Oregon coast since the terrace only varies in elevation from 11 ± 3 m to 20 ± 3 m above MSL.

The monotony and low rate of deformation of terraces in northern Oregon is in contrast to terraces in southern Oregon and northern Washington which have more deformation. The reasons for this type of deformation probably has to do with tectonic setting. The northern Oregon coast is approximately 120 km from the trench and the trench runs parallel to the coastline. This configuration may result in the subducting slab being deeper under the northern Oregon coast then at other locations along the Cascadia margin.

Several features of the terraces on the northern Oregon coast need further work to obtain a better understanding of their significance. First, detailed mapping of terrace deposits is needed to better understand their depositional environments. Such a study would be able to determine the late Pleistocene regional sedimentary framework of the study area. Liquefaction features within terrace sediments also need additional study. At present the origin and meaning of these features are poorly understood. Continued studies of liquefaction features within the Pleistocene deposits and also their identification within Holocene deposits may
provide another direct line of evidence for large earthquake events which cause shaking and liquefaction of sediments.
SELECTED REFERENCES


Ando, M., and Balazs, E.I, 1979, Geodetic evidence for aseismic subduction of the Juan de Fuca plate: Journal of Geophysical Research, v. 84, p. 3023-3028.


Kelsey, H.M., 1990, Late Quaternary deformation of marine terraces of the Cascadia subduction zone near Cape Blanco, Oregon: Tectonics, v. 9, p. 983-1014.


Munsell, 1990, Soil Color Charts: MacBeth Division of Kollmorgan Instruments Corporation, Baltimore.


APPENDIX

DESCRIPTION OF DRILL CORE SEDIMENTS

Hanson Site

(cm)
0-85 fill dirt
85-174 modern soil
174-375 tan mud with rust mottles
375-405 fine sandy mud
405-483 clean sand; abundant mica
483-493 peat
493-566 light brown clean sand
566-591 gray mud
591-631 peat; gradual lower and abrupt upper contact
631-656 gray barren mud
656-666 peat; gradual lower and abrupt upper contact
666-681 gray barren mud
681-617 peat; gradual lower and abrupt upper contact
617-647 gray barren mud
647-652 peat
652-1682 clean sand; abundant quartz
1682 weathered siltstone

Fish Site

(cm)
0-82 soil
82-233 tan weathered mud
233-379 tan weathered fine sandy mud
379-419 gray fine sandy mud
419-422 peaty mud
422-428 finely laminated fine sandy mud
428-430 peaty mud
430-440 gray barren mud
440-450 peaty mud
450-496 gray barren mud
496-515 fine sandy mud
515-534 gray barren mud
534-577 fine sandy mud
577-635 gray barren mud
635-651 peat; gradual lower and abrupt upper contact
651-691 rooted mud
691-739 gray barren mud
739-763  finely laminated fine sandy mud
763-765  peat; gradual lower and abrupt upper contact
765-774  gray barren mud
774-810  finely laminated fine sandy mud
810-811  peat
811-867  gray barren mud
867-929  silty mud
929-931  peaty mud; gradual lower and abrupt upper contact
931-965  gray barren mud
965-998  finely laminated fine sandy mud
998-1045 finely laminated fine sandy mud
1045-1046 peat
1046-1123 finely laminated fine sandy mud
1123-1128 peaty mud; gradual lower and abrupt upper contact
1128-1173 gray barren mud
1173-1188 finely laminated fine sandy mud
1188-1189 peaty mud
1189-1200 gray barren mud
1200-1220 fine sandy mud
1220-1222 peat
1222-1264 fine sandy mud
1264-1293 wood (possible stump)
1293-1443 muddy fairly well rounded gravel
1443-1446 peaty mud; gradual lower and unclear upper contact
1446-1488 gray barren mud
1488-1494 fine sandy mud
1494-1502 gray barren mud
1502-1512 finely laminated fine sandy mud
1512-1515 weak peaty mud
1515-1520 gray barren mud
1520-1523 peaty mud; gradual lower and abrupt upper contact
1523-1530 gray barren mud
1530-1536 peat; gradual lower and abrupt upper contact
1536-1553 gray barren mud
1553-1556 peat; gradual lower and abrupt upper contact
1556-1564 gray barren mud
1564-1565 peat
1565-1589 gray barren mud

**Niflis Site**

(cm)

0-78  soil
78-156 gray mud
156-589 tan mud with rust mottles
589-727 gray mud
727-735 peat; gradual lower and abrupt upper contact
735-787 gray barren mud
787-791 peat; gradual lower and abrupt upper contact
791-796 gray barren mud
<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
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<tr>
<td>796-799</td>
<td>peat; gradual lower and abrupt upper contact</td>
</tr>
<tr>
<td>799-857</td>
<td>fine sandy mud (organic detritus from 830-833)</td>
</tr>
<tr>
<td>857-869</td>
<td>organic detritus</td>
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<tr>
<td>869-884</td>
<td>finely laminated fine sandy mud</td>
</tr>
<tr>
<td>884-888</td>
<td>peat; gradual lower and abrupt lower contact</td>
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<tr>
<td>888-912</td>
<td>finely laminated fine sandy mud</td>
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<tr>
<td>912-918</td>
<td>peaty mud; gradual lower and abrupt lower contact</td>
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<tr>
<td>918-956</td>
<td>gray barren mud</td>
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<tr>
<td>956-957</td>
<td>weak peaty mud</td>
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<td>957-990</td>
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<td>990-1017</td>
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<td>1017-1022</td>
<td>peat; gradual lower and abrupt upper contact</td>
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<td>1047-1050</td>
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<tr>
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<td>rooted mud</td>
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<td>1094-1103</td>
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<td>1103-1222</td>
<td>finely laminated fine sandy mud</td>
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<tr>
<td>1222-1224</td>
<td>peaty mud; gradual lower and abrupt upper contact</td>
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<td>1224-1229</td>
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<td>1231-1239</td>
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<td>1239-1241</td>
<td>silty mud</td>
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<tr>
<td>1253-1255</td>
<td>silty mud</td>
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<tr>
<td>1255-1258</td>
<td>gray mud</td>
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<tr>
<td>1258-1260</td>
<td>peaty mud; gradual lower and abrupt upper contact</td>
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<td>1260-1267</td>
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<td>1363-1373</td>
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<td>1467-1477</td>
<td>weakly rooted mud</td>
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<td>finely laminated fine sandy mud</td>
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