Evidence of precursor events for mega-thrust earthquakes on the west coast of North America

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Abstract

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In May 1964 a 9.2 magnitude (on the Richter scale) earthquake occurred on the coast of Alaska. Since then, research has shown evidence of precursors to the earthquake using both foraminifera and diatoms, thereby detailing a previously unknown sequence of events. This project focuses on a marsh environment lying farther south in Netarts Bay, Oregon, USA. Netarts Bay was also reported to have precursor earthquake events that were discovered using only diatom analysis.

The Alaska earthquake offers the possibility to compare a known sequence of events with the geologic record. However, the Netarts Bay marsh has experienced no modern earthquake that could be used for comparison, but the nature of mega-thrust earthquakes means that the modern and ancient events should be physically similar. One of the previously cores sites was re-cored to resample and re-examine transition zones using foraminifera and thecamoebians. The benefit of using a previously sampled site is that the core has already been dated and zones of transition have already been identified lithologically.

The core used in this study has four visually distinguishable transitions. Previous dating indicates that such events have occurred over a period of ca. 3000 years. Of the four transition zones examined, transitions 2 and 3 display strong precursor evidence to mega-thrust earthquakes. Transition 1, the only transition that displayed an emergence precursor may be seismic but is most likely non-seismic and the result of sediment infilling. Transition 4 is a weaker version of transitions 2 and 3, which all depict a subsidence precursor event.

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Chapter One: Introduction

1.1 Thesis statement and scope

Prior work along the west coast of North America (e.g. Atwater, 1987, 1995, 1997; Shennan et al., 1998a,b) has shown that records of periodic occurrences of major earthquakes are found in coastal sediments. The major representations are large (1-2 m) instantaneous subsidence intervals that are composed of freshwater or marine peat to subtidal coastal facies. Micro-subsidence of marsh levels just prior a major earthquake event has been documented in Alaska using microfossils (Shennan et al., 1999). This land movement is suggested to be the result of stress load associated with ocean-continent subduction boundaries, producing a small, localized subsidence at forest marsh level that allows saline water to trangress further into the marsh, at least one year prior to a great earthquake. The utilization of microfossils, specifically foraminifera and thecamoebians, as indicators of precursor events for mega-thrust earthquakes, takes advantage of their sensitivity to physical and chemical changes in their environment.

The scope of this project is to evaluate whether microorganisms can be used as indicators of earthquake precursor events at marsh level environments in Netarts Bay, Oregon. Previous work at this site allows for comparison of sequences and dates, which is an important component of this project. The project incorporates a three-metre core from the Netarts Bay salt marsh in northern Oregon. The site of the project is located on the west coast of North America where the specific tectonic situation enables great earthquakes to occur (Atwater, 1987; Plafker and Berg, 1994). Although, the core is only three meters long, it crosses several earthquake transition zones and represents ca. 3000 years of this site's history (Darienzo, 1991; Darienzo et al., 1994; Shennan et al., 1998b).

1.2 Structural thrust zone region

Netarts Bay, Oregon and surrounding coastal environments have a long history of great earthquakes and tsunamis (Atwater, 1987; Atwater et al., 1995; Nelson et al., 1995, 1996). Just offshore from the bay lies a fault, which runs from Alaska south through northern California before veering off into the Pacific Ocean.

The Cascadian subduction zone is the convergent boundary between the large North American continental plate, the small Juan de Fuca (oceanic) plate and the Gorda (oceanic) plate to the south (figure 1.1) (Plafker and Berg, 1994). The smaller oceanic plates are being subducted beneath the North American plate at a rate of 2.5-3 centimetres per year. As the Juan de Fuca and Gorda plates converge into North America, stress accumulates. Earthquakes are caused by the abrupt release of that slowly accumulated stress (figure 1.2). These earthquakes originate from deep within the downward-going crust and are on the order of 8 or more moment magnitude on the Richter scale (Shennan et al., 1998a). Subduction zones are areas where frequent shallow earthquakes occur and less frequent deep focus earthquakes. If the earthquake occurs offshore, they may generate tsunamis, which are large shock waves that cause major coastal destruction and deposit substantial quantities of sediment instantaneously on surrounding coasts. The Pacific coast is also an area of high volcanism which occurs on the overriding North American continental plate (Plafker and Berg, 1994).

Figure 1.1

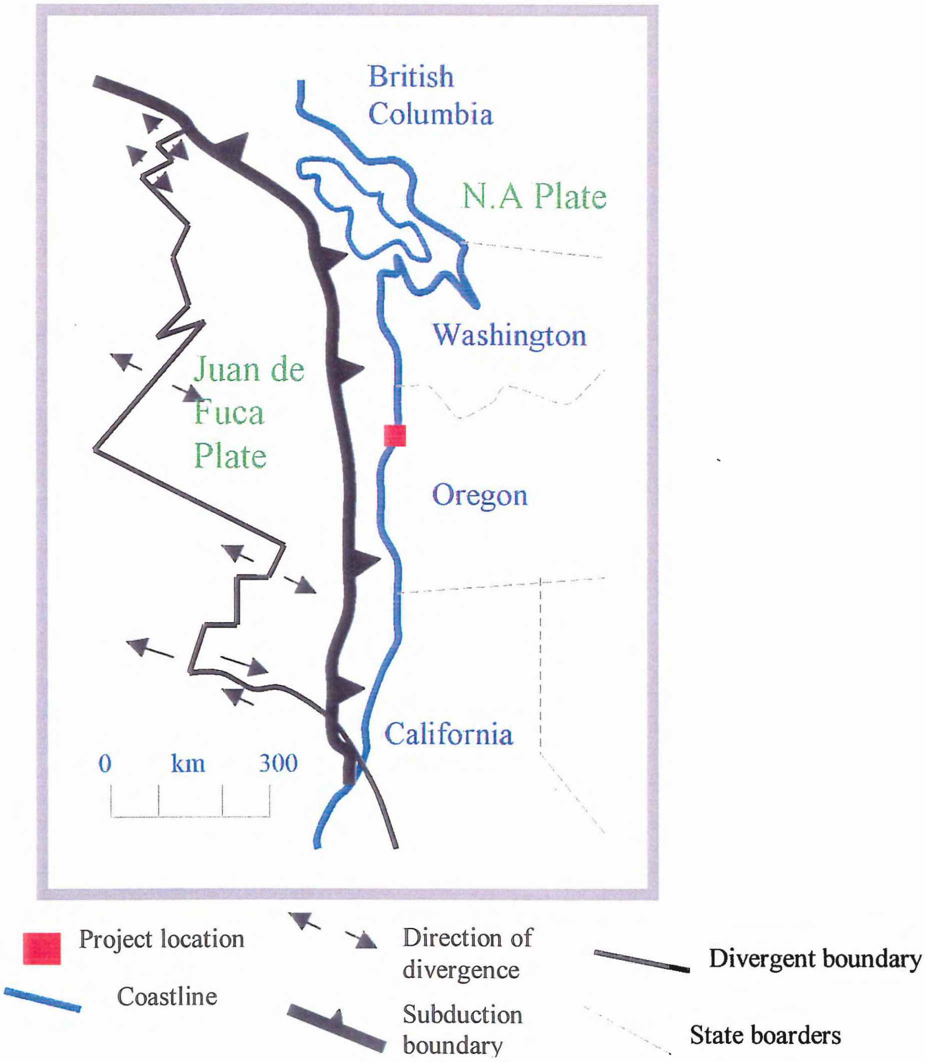


Figure 1.1.
Subduction boundary between the down-going Juan de Fuca plate under the North America plate. The red box represents the location of this project area. Modified from Shennan et al., 1998b

Figure 1.2

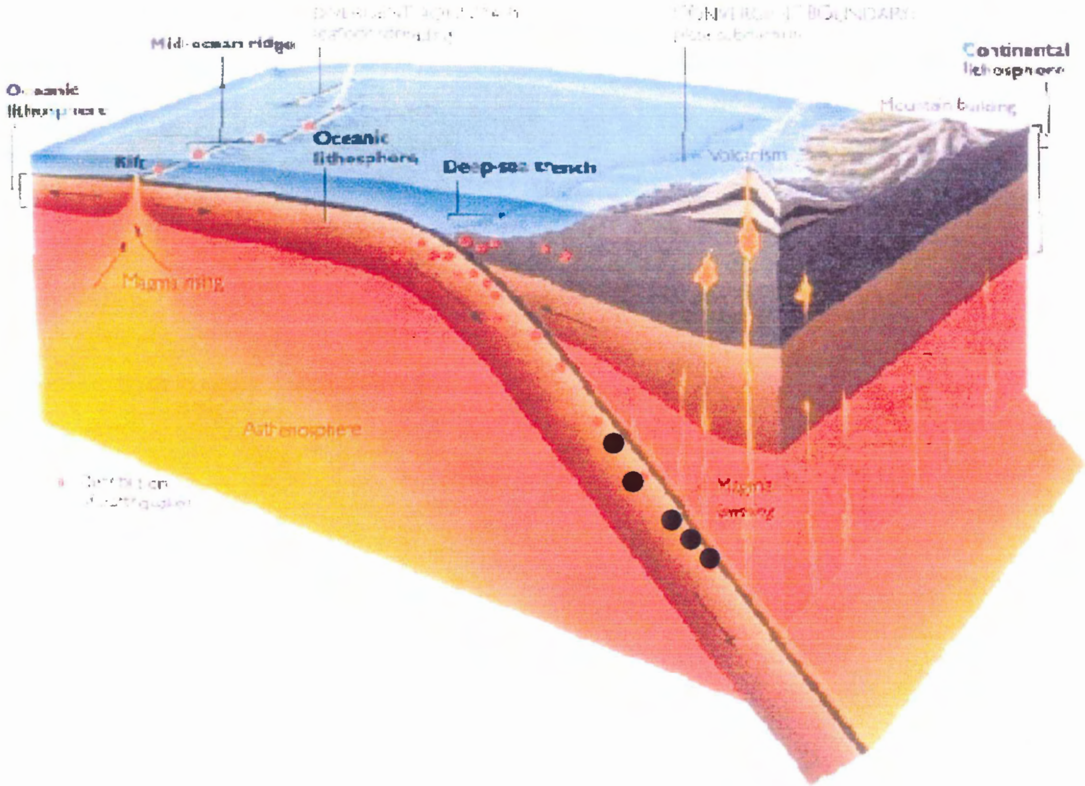


Figure 1.2.
3D representation of an oceanic plate being subducted under a continental plate and associated geologic events. Black circles represent deep mega-thrust earthquakes. Smaller red circles represent shallow earthquakes
(Press and Siever, 1997)

Figure 1.3

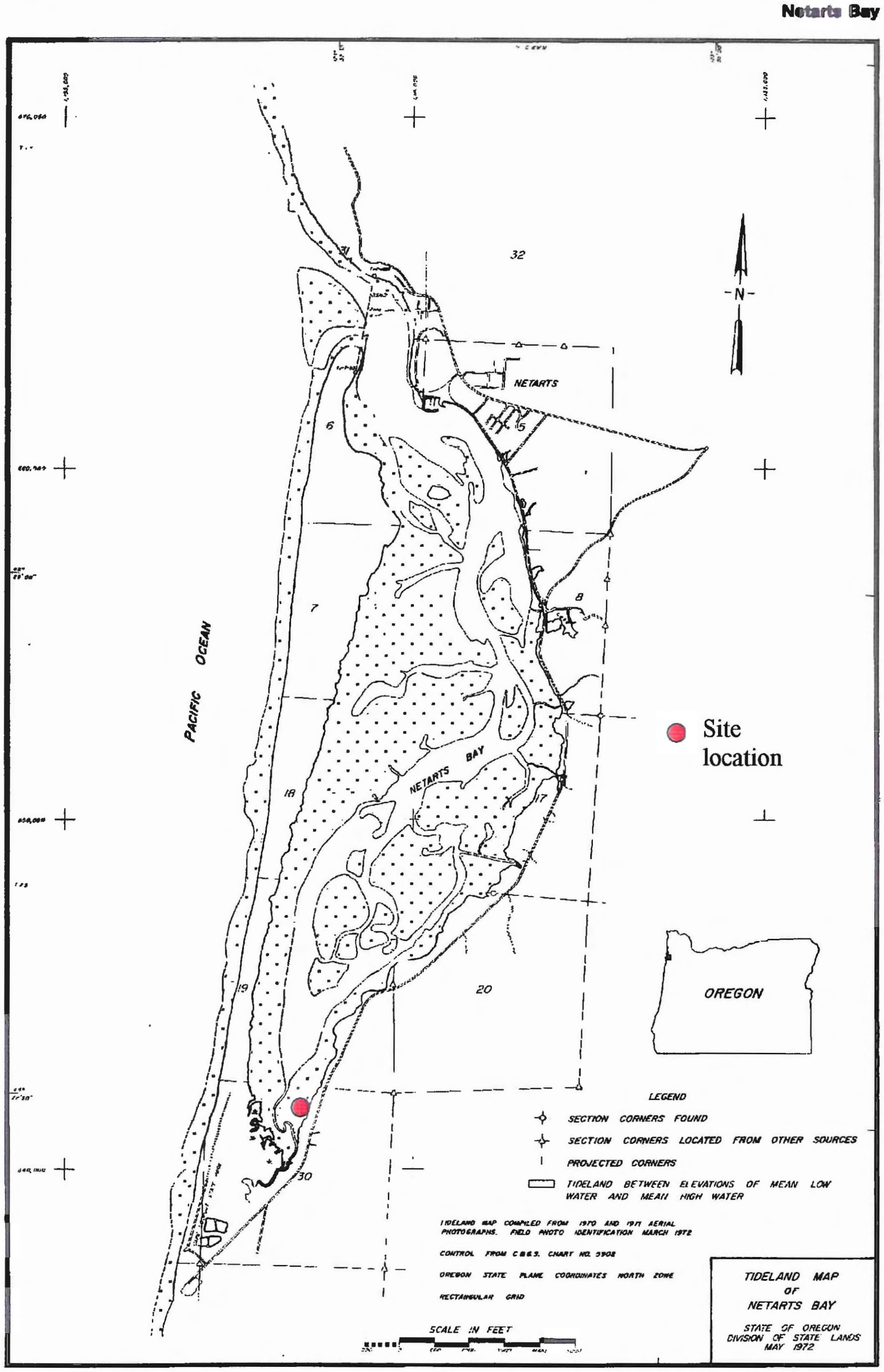


Figure 1.3.
Tideland of Netarts Bay, Oregon. Dotted areas reflect tideland between mean low tide and mean high tide.
-modified from Cox, W. (1973)

1.3.1 Marsh level

A minor shift in the land level can change the sedimentary environment and thus affect organisms drastically, because salt marshes are in equilibrium with tidal fluctuations. These events are recorded as a slight vertical land movement that can only be detected by looking at the biostratigraphic and lithostratigraphic record. Due to the direct relationship between land movement, salinity and change in microorganism assemblages, the rapid shift from one assemblage to another may be correlated with a tectonic movement of subsidence or uplift, and therefore may imply an earthquake (Nelson et al., 1996).

The distribution of coastal marsh and tidal flat communities is closely related to elevation and local tidal conditions. It is for this reason that such environments can be divided into low, middle and high marsh. If at each marsh level the modern assemblage is known with precision then preserved fossils can be indicative of past elevation at a specific site (Scott & Medioli, 1978, 1980a,b; Jennings & Nelson, 1992; Scott et al., 2001).

The core used with this project corresponds to core number 18 in Shennan et al. (1998b), and is located at high marsh around the mean high water level (figure 1.4 Shennan map). In general this corresponds to mean high tide. This part of Netarts Bay receives salt water influx, usually only once a day, and at the very edge of the high tide level (Shennan et al., 1998b).

Figure 1.4

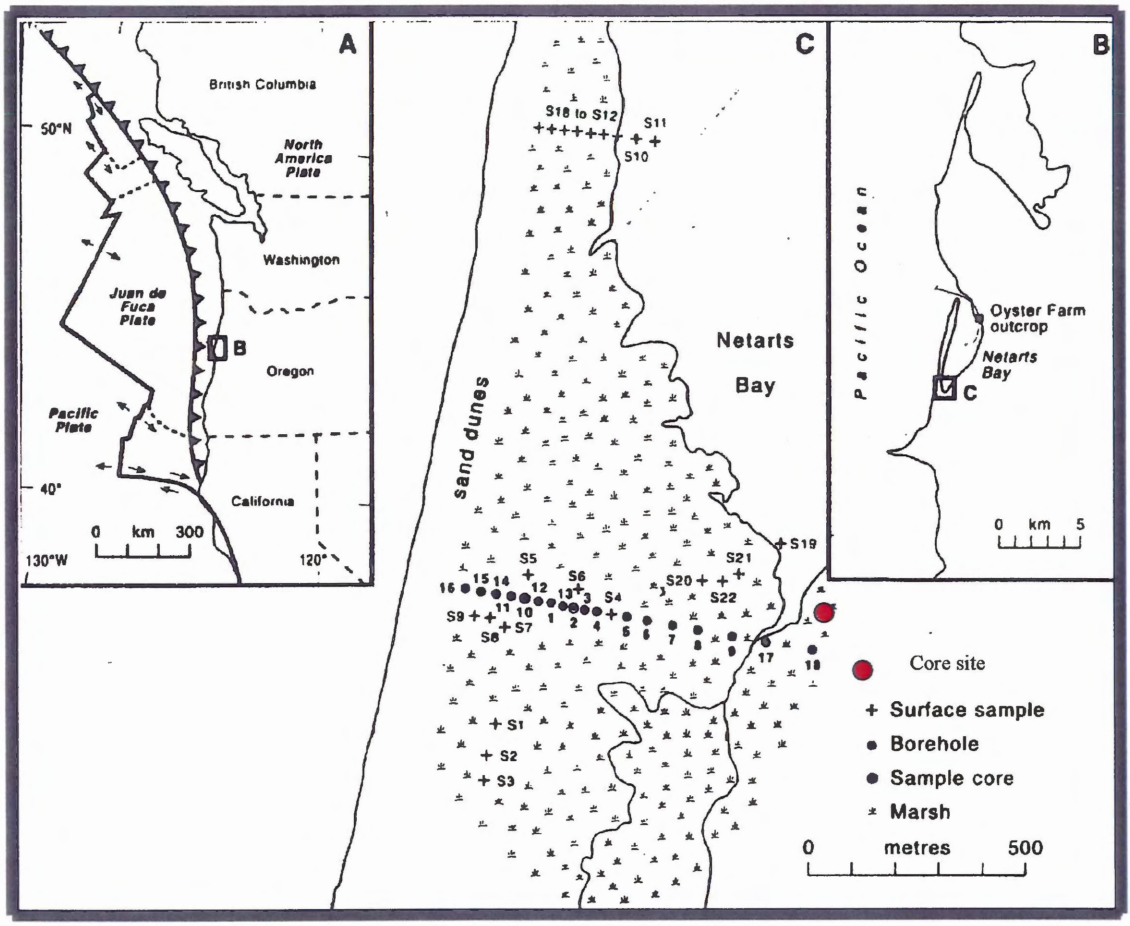


Figure 1.4.
Shennan et al. (1998b) tectonic situation map (A), coastal site map (B), and sample and core locations map (C). Core 18 (Shennan, 1998b) in black corresponds to the core used in this study, shown in red.

1.3.2 Tide

The tidal range of the inlet is approximately two metres. The tidal range remains fairly constant, dependent on onshore or offshore wind generated currents. Ocean currents do not play a large role in Netarts Bay because it is protected from the open ocean by a spit running (2 m above mean tide) almost the entire length of the bay (figure 1.3) (Shennan et al., 1998b).

1.4 Background

Earthquakes are common around the Pacific Rim region and pose a great threat to its population, as the past few decades demonstrate in nearly every Pacific Rim country (figure 1.5). Two types of study can assist in determining the probability of future earthquakes: the study of recent and historic fault movement (e.g. Atwater, 1987), and the detection of precursor events to earthquakes (Shennan et al., 1998b, 1999).

In several places around the Pacific Rim, episodic seismic events are recorded in sedimentary deposits of coastal environments. These events are often associated with vertical land movement, salt marsh foraminiferal assemblages, and local coastal vegetation that are sensitive to changes in the basic ecological factors, such as salinity and elevation, that these land movements induce (Nelson et al., 1995, 1996; Jennings & Nelson, 1992, Shennan et al., 1998a).

A record of the changing elevation of a marsh through time can be obtained by analyzing changes in the abundance of indicator species in a sedimentary sequence. Abrupt subsidence/uplift just after great earthquakes is recorded in estuarine environments by sharp changes in the lithology and biofacies of the intertidal sediments. However, more subtle movements, that might be key precursors to a

Figure 1.5

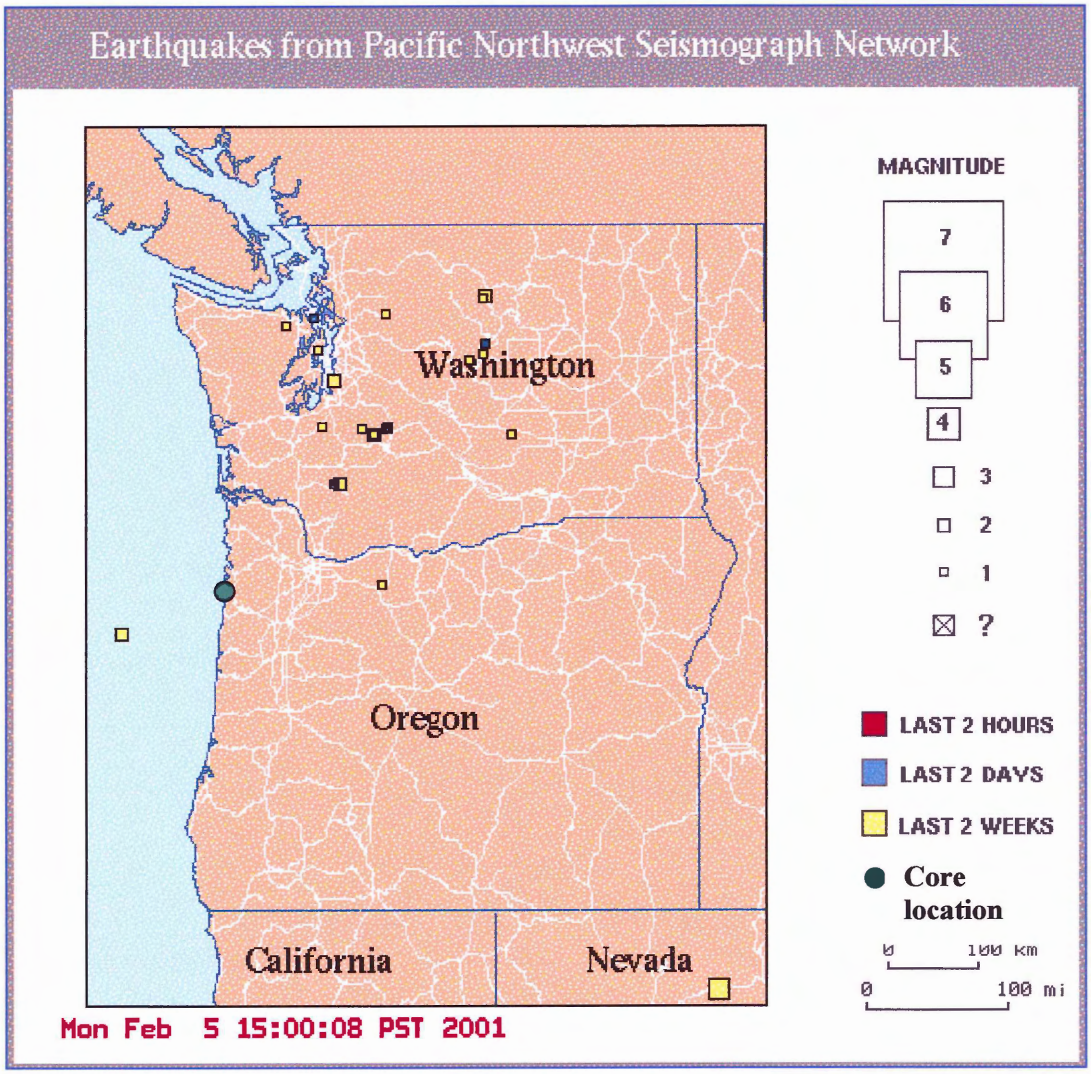


Figure 1.5.
Seismic events in Washington, Oregon, northern California and Nevada during the period of January 22, 2001 to February 5, 2001.
-http://www.geophys.washington.edu/recenteqs/.

major earthquake, require detailed analyses of less obvious boundaries in sediment deposits that predate a major event (Shennan et al., 1998b, 1999).

1.5 Foraminifera and thecamoebians as indicators

The Testate Rhizopods are a superclass to three classes, Lobosa, Filosa, and Granuloreticulosa. The first class contains the order Thecolobosa (thecamoebians) and the last class contains order Foraminiferida (foraminifera). These two groups of microfossils are utilized in the project as indicators. Foraminifera and thecamoebians are one-celled animals. They form a shell or test, which remains as a fossil in the sediment. Foraminifera occupy every marine environment from high-high water down to the deepest parts of the ocean, and often over these areas occur in relatively high abundance. Thecamoebians are widely distributed in freshwater environments (Scott et al., 2001).

These two groups have a great advantage over most other biological indicators because they leave an abundant fossil record that permits the reconstruction of the environmental history of a site in the absence of original physio-chemical baseline data (Scott et al., 2001).

1.5.1 Foraminifera test

The tests of foraminifera can be composed of several types of material. The type and composition of the test can indicate a variety of factors about the organism and its surrounding environment. Species that create their own test (autogenous) of calcium carbonate, do so only in conditions conducive to carbonate preservation. Those conditions include; high pH, low organic matter, high oxygen, and high temperature (Scott et al., 2001).

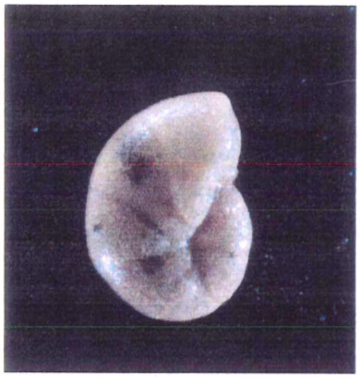
A different type of foraminifera creates its test by cementing detrital material together; this type of species is often called "agglutinated" or "arenaceous" (figure 1.6). The agglutinated species are the more primitive species of foraminifera, and they also have the ability to survive in more extreme conditions where carbonate is low or not present at all. These environments include lowered salinity, low oxygen, cold water, and low pH. In general, as salinity and temperature increase, agglutinated species are replaced by calcareous foraminifera (Scott et al., 2001).

1.5.2 Thecamoebian test

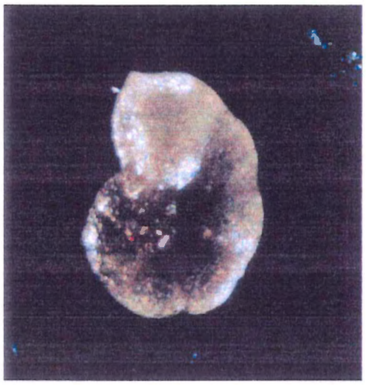
Thecamoebians are often referred to as the equivalent, in freshwater, of foraminifera. Thecamoebians can also generate their own test from the surrounding material (Medioli and Scott, 1983). Autogenous tests are either solid silica or a complex amalgamation of organic matter, or built of plates secreted by the organism; these plates are referred to as idiosomes (figure 1.7) (Scott et al., 2001). The majority of thecamoebians that are preserved in the fossil record are made of agglutinated tests consisting of foreign particles cemented together. These particles are picked up from the surrounding area and therefore reflect the surrounding environment. Thecamoebians occupy all fresh water environments including tree bark and moss (Scott et al., 2001).

Figure 1.6 Foraminifera

Miliammina fusca



Haplophragmoides wilberti



Trochammina macrescens f. polystoma

Trochammina macrescens f. polystoma

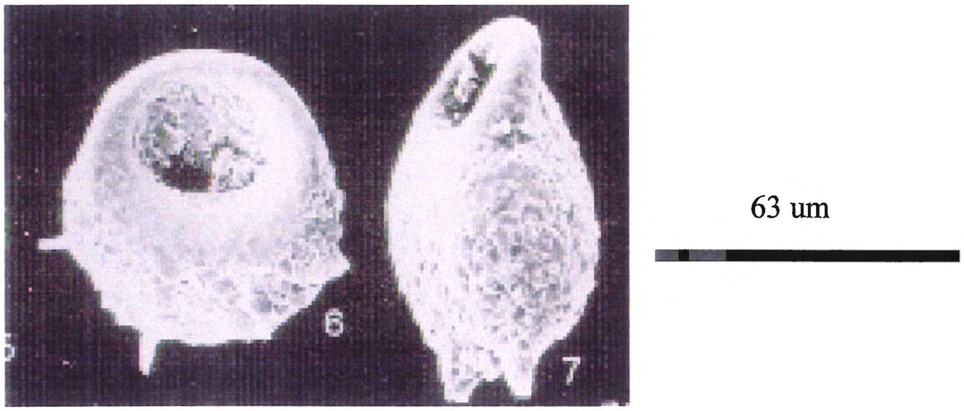
Trochammina macrescens f. macrescens

63 um

-Scanning light photographs of agglutinated foraminifera found in this study. *Miliammina fusca* and *Trochammina macrescens f. polystoma* represent a low marsh zone while *Trochammina macrescens f. macrecsens* and *Haplophragmoides wilberti* represent a high marsh zone. The difference between the *Trochammina macrescens f. polystoma* and the *Trochammina macrescens f. macrescens* is that the *Trochammina macrescens f. polystoma* has several apertures. (all photographs from Scott et al., 1990)

Figure 1.7.

Thecamoebians



Centropyxis aculeata

Centropyxis constricta

-Scanning electron micrographs of agglutinated thecamoebians. These species dominate fresh water environments. (photographs from Medioli and Scott, 1983)

Chapter Two: Previous work

2.1 Oregon and surrounding states

2.1.1 Diatom and Pollen analysis in Netarts Bay, Oregon

Netarts Bay is not an area unknown to scientific research. Although the Bay has maintained a relatively pristine environment, several similar-type projects have already been conducted. One paper in particular, on which my project relies heavily, is that of Shennan et al. (1998b) on tidal marsh stratigraphy, sea-level change and large earthquakes focusing especially on submergence events during the last 3500 years at Netarts Bay, Oregon. Shennan et al. (1998b) is a second investigation (the first being Shennan et al., 1998a) of applying the methods and scientific theory to sea-level investigation in northwestern Europe to test an "earthquake deformation cycle", a model of coseismic land subsidence followed by land uplift during the interseismic strain accumulation period. This method is applied to explain the alternating peat-mud couplets of the late-Holocene that are found in many of the estuaries along the west coast of North America.

The researchers used lithological, pollen and diatom analysis to record different types of submergence associated with peat-mud couplets over the last 3500 years. Recent studies along the Cascadian Subduction zone have associated the presence of these peat-mud couplets with repeated large-scale, high magnitude earthquakes. A series of 18 vibracores and 22 surface samples were taken by Shennan et al. (1998b) to evaluate the earthquake deformation cycle in Netarts Bay.

Of the 18 cores taken, two cores containing five peat-mud couplets were examined with pollen and diatoms used as marsh level indicators. The first (base up) couplet revealed a gradual change suggesting a transition from an area of high marsh to a low marsh environment. In the second couplet, before a transition to a low marsh area where the changes in diatom species and pollen types represent evidence of more frequent tidal flooding of high-brackish marsh prior to the deposition of silt and clay. The third and fourth couplets display differing results from the two preceding couplets, representing the accumulation of organic material within a shallow body of fresh or low salinity water. The fifth couplet reveals a shallow body of water with an increasing frequency of tidal inundation up-section (Shennan et al., 1998b).

Shennan et al. (1998b) apply five types of evidence, which may be used to test the hypothesis of coastal subsidence during great earthquakes at the Cascadian subduction zone, taken from Nelson et al. (1996). They include lateral extent of peat-mud couplets, synchroneity of submergence, coincidence of submergence with tsunami deposits, rapidity of submergence, and amount of submergence. I have not considered the first two tests because I am only examining one core in the marsh.

Shennan et al. (1998b) evaluated whether the minerogenic deposits overlying many of the peat layers observed within the cores were concurrent with tsunami events. The diatom and pollen analysis revealed that the assemblages in the coarser minerogenic sediment overlying the peat, are generally similar to those in the underlying and overlying sediments. This reflects a local-scale sediment change within the estuary. The authors concluded that evidence of tsunami deposits at Netarts Bay is not convincing and that other evidence would provide a stronger test of the hypothesis of coastal subsidence during great earthquakes. What must be noted here is that diatoms and pollen are not as sensitive to changes in elevation relative to tidal level or as indicative of marsh zonation as foraminifera and thecamoebians.

The fifth method of testing coastal subsidence is the measurement of the amount of subsidence. This can be evaluated by comparing the environment at the top of a submerged peat layer with the lower part of the overlying minerogenic layers, excluding the tsunami deposit (post earthquake event), where present. The peat-mud couplets in Netarts Bay revealed submergence levels ranging from 10 cm to 1 m (Shennan et al., 1998b).

When applying the previously mentioned information to the earthquake deformation cycle, it follows that great earthquakes create a coseismic submergence followed by uplift during the interseismic strain accumulation period. Shennan et al. (1998b) discovered that the techniques of identification of the pre-seismic stage are lacking for their project because pollen and diatom assemblages do not reflect the small-scale changes in the local environment required to see the subtle precursor event. They suggested that other microfossil techniques, notably use of foraminifera, would provide promising and better-constrained solutions. They suggested that small rapid changes in sea level can be produced by a variety of non-seismic processes, including barrier breaching (Shennan et al., 1998b).

During the interseismic period of the earthquake deformation cycle, it is unlikely that the rates of relative sea-level rise and sedimentation remain constant. Netarts Bay stratigraphy suggests there are submergence events from pre-seismic relative sea-level rise followed by small amounts of coseismic subsidence. The conclusion of Shennan et al. (1998b) is that it is difficult to distinguish between seismic and non-seismic causes of submergence using pollen and diatoms, but that the identification of sea-level tendencies prior to, and following, submergence provides insight into the process of relative sea-level change accompanying the earthquake deformation cycle. Although the paper does provide evidence of pre-seismic reductions in the rate of sea-level change, the subject does require better temporal resolution before an assessment could be made as to how such reductions relate to the timing and magnitude of earthquakes (Shennan et al., 1998b).

2.1.2 Evidence of great earthquakes in western Washington

Atwater (1997) noted that, by 1995, evidence of subsidence, tsunamis, and shaking had been found at more than a dozen sites along the Pacific coast from northern California to southern British Columbia.

The buried spruce forests of coastal Washington give evidence of submergence. A dead forest or "ghost forest" can occur in three ways: 1) simple submergence to below high tide resulting in dead forest protruding through the tidal marsh (figure 2.1.a); 2) deposition caused by storm, flood, or tsunami where the forest floor builds above high tide (figure 2.1.b); and, 3) coseismic submergence, burial, and then exhumation in a five-part stage beginning with living forest above high tide (figure 2.1.c), with coseismic submergence bringing the forest below high tide and killing the forest. The ghost forest then rises (relaxation) slightly after the earthquake while being buried in a tidal flat. Deposition of sediment continues until the surface is above high tide and plants begin to grow again. At this point the ghost forest stumps are completely buried. Exhumation occurs in tidal creeks where tidal creek migration reveals once-buried stumps below high tide or in cores where repetitive forest sequences are revealed (Atwater, 1997).

Evidence from coastal Washington demonstrates that submergence of the lowlands happened so quickly that it is better explained by abrupt lowering of the land than the gradual rise in sea level. Evidence of the abruptness of the submergence is evident through outer annual growth rings of a tree. If the outer rings show no little or no thinning, this suggests that the tree's death was sudden (Atwater, 1997).

Great subduction zone earthquakes are almost always followed by tsunamis, substantial sand deposits, which in stratigraphic section, abruptly cut off whatever

Figure 2.1.

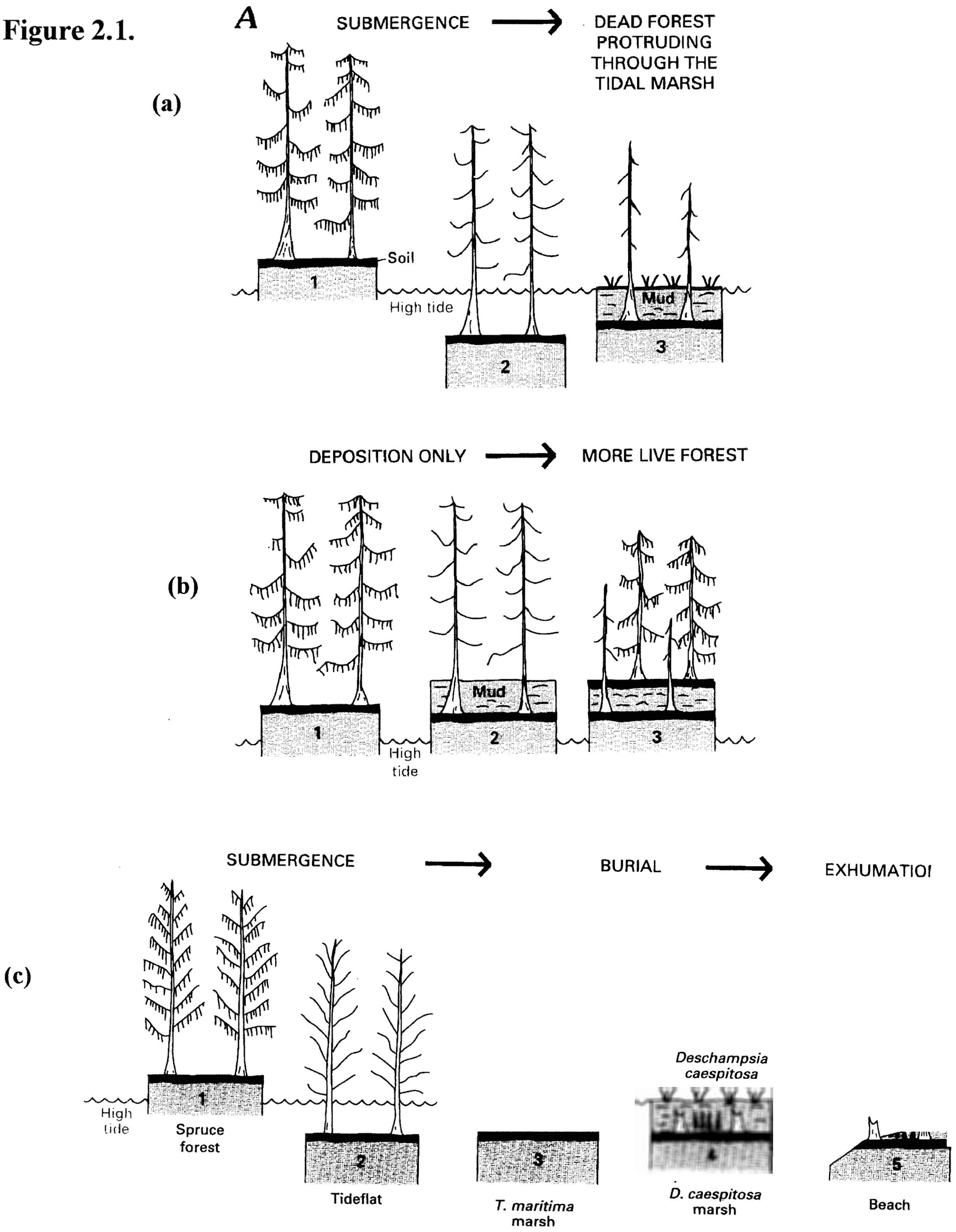


Figure 2.a,b,c.
(a) decomposition triggered by tidal submergence.
(b) deposition by storm, flood, or tsunami.
(c) inferred coseismic sequence of events leading to burial and exhumation.
(Atwater, 1997)

environment was thriving prior to the earthquake (Atwater, 1997). This type of event is common in the core examined for this project.

As the above deposits are recorded century after century, these buried lowland soils give insight into how much time may elapse between successive great earthquakes. Atwater (1997) suggests that there remain many challenges in reconstructing the history of great earthquakes at the Cascadian subduction zone. One challenge is to show which buried soils correspond with great earthquakes; buried soils at some sites may only be recording non-seismic changes in tide level or smaller earthquakes (Nelson et al., 1996).

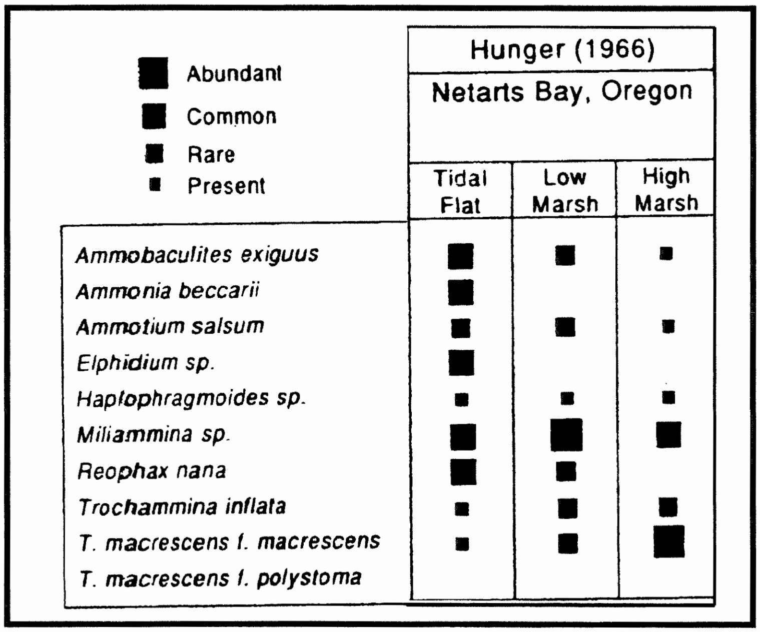
The most precise radiocarbon dating limits the time of plant death to the same few decades close to A.D. 1700 in some core sequences from southern Washington, northern Oregon, and northern California. This similarity can be explained by either a swift series of magnitude 8 earthquakes or the possibility of a single magnitude 9 earthquake event (Atwater, 1997). Satake et al. (1996) give evidence for an AD 1700 mega-thrust earthquake along the Cascadia subduction zone as the cause of the AD 1700 tsunami historically recorded in Japan. The lack of major earthquake evidence in South America, Alaska or Kamchatka leaves Cascadia as the most likely source of the tsunami. The tsunami heights in Japan for this event are approximately 0.3 m, which allowed a magnitude estimate of ca. 9 on the Richter scale for the AD 1700 earthquake. The tsunamis in Japan were recorded and documented as "unknown source" and placed on January 27-28 1700 by the Gregorian calendar (Tsuji, 1987). It is important to note that transition 1 in this project may represent ca. 300 years ago (Atwater, 1997).

2.1.3 Foraminiferal zones in Oregon marshes

Jennings and Nelson (1992) characterized each floral zone of Oregon marshes with the specific foraminiferal assemblage particular to that zone. These zones and accompanying assemblages were then compared to similar areas on the east and west coast of North America. Some of the factors that affect marsh distribution include, most importantly, the duration and frequency of intertidal exposure, and salinity. Other less influential factors include temperature, surface moisture, availability of nutrients, water energy, and substrate texture (Phleger, 1970). Scott et al. (1996) collected less detailed data from the entire west coast of North America and demonstrated that there is a vertical relationship occurring along the entire western margin perhaps excluding Alaska.

Jennings and Nelson (1992) reviewed marsh zonation in Oregon building upon the Hunger (1966) account of foraminiferal distribution (Table 2.1), and established that three zones exist: tidal flats, low marsh, and high marsh. Tidal flats are characterized by the genera *Ammobaculites, Ammonia, Ammotium, Elphidium, Miliammina, and Reophax.* Low marsh contains *Miliammina fusca, Reophax nana, Trochammina inflata, Trochammina macrescens f. macrescens, Ammobaculities* and *Ammotium*. High marsh is distinguished by the dominance of *Trochammina macrescens f. macrescens, Miliammina fusca, and Trochammina inflata* (Hunger, 1966). Jennings and Nelson (1992) added an additional floral zone to the Oregon marshes, which lies vertically above high marsh as the upland zone; generally this area is barren of foraminifera. They also noted that boundaries between zones are fairly gradational, especially with reference to the boundary between low and high marsh. This is a result of the low elevation gradients in the middle parts of Oregon marshes (Jennings and Nelson, 1992).

Table 2.1

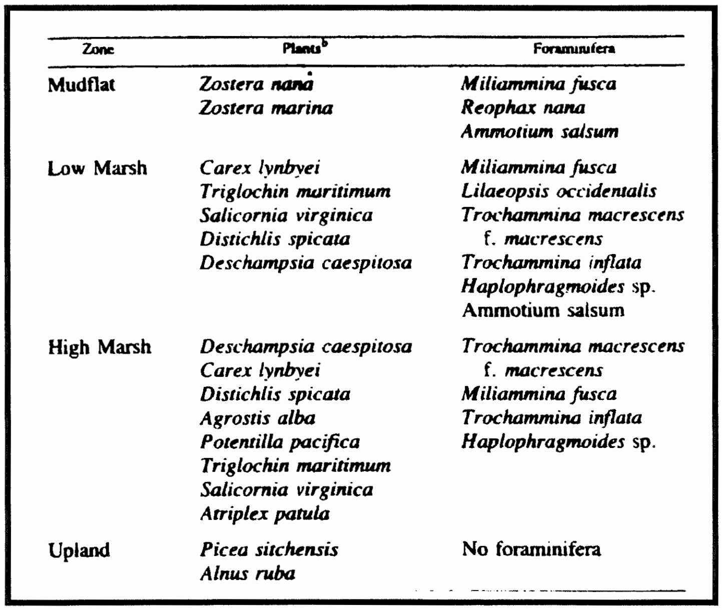


⬛ Abundant
■ Common
◾ Rare
▪ Present

	Hunger (1966) Netarts Bay, Oregon		
	Tidal Flat	Low Marsh	High Marsh
Ammobaculites exiguus	■	◾	▪
Ammonia beccarii	■		
Ammotium salsum	◾	◾	▪
Elphidium sp.	■		
Haplophragmoides sp.	▪	▪	▪
Miliammina sp.	■	⬛	■
Reophax nana	■	◾	
Trochammina inflata	▪	◾	◾
T. macrescens f. macrescens	▪	◾	⬛
T. macrescens f. polystoma			

Table 2.1.
Relative abundance of foraminifera species in marsh and tide flat environments of the Pacific Northwest as described by Hunger (1966) in (Jennings & Nelson, 1992).

Table 2.2



Zone	Plants[b]	Foraminifera
Mudflat	*Zostera nana* *Zostera marina*	*Miliammina fusca* *Reophax nana* *Ammotium salsum*
Low Marsh	*Carex lynbyei* *Triglochin maritimum* *Salicornia virginica* *Distichlis spicata* *Deschampsia caespitosa*	*Miliammina fusca* *Lilaeopsis occidentalis* *Trochammina macrescens* f. *macrescens* *Trochammina inflata* *Haplophragmoides* sp. Ammotium salsum
High Marsh	*Deschampsia caespitosa* *Carex lynbyei* *Distichlis spicata* *Agrostis alba* *Potentilla pacifica* *Triglochin maritimum* *Salicornia virginica* *Atriplex patula*	*Trochammina macrescens* f. *macrescens* *Miliammina fusca* *Trochammina inflata* *Haplophragmoides* sp.
Upland	*Picea sitchensis* *Alnus ruba*	No foraminifera

Table 2.2.
Vascular plants and foraminiferal species characteristic of elevational zones common in Oregon marshes.
(Jennings & Nelson, 1992; Jefferson, 1975; Frenkel et al., 1978; Hoffnagle etal., 1974, 1976)

Jennings and Nelson (1992) list in table format the species of plants and foraminiferal assemblages in correlation to zones within the marsh (table 2.2). This table has strong similarities to that of Hunger (1966). They compared the foraminiferal assemblages in marshes from central Oregon with assemblages in British Columbia, Nova Scotia, and Massachusetts. The following is a summary of their findings, as seen in figure 2.2. High marsh in four areas can be recognized by the dominance of *Trochammina macrescens f. macrescens* and in most areas, also *Trochammina inflata* (Scott & Medioli, 1980b). *Miliammina fusca and Haplophragmoides* (both species) are also species that are frequently found in the high marsh zone. High-marsh assemblages display a sharp drop in *Miliammina* and an increase in the percentage of *Haplophragmoides* (usually a result of low salinity) and are often characterised by peaks in the percentage of *Trochammina inflata* (Jennings and Nelson, 1992).

Low marsh has been separated into two zones, lowest low-marsh and low marsh. Scott & Medioli (1980b) differentiate between the two subzones in Nova Scotia with low marsh containing relatively equal numbers of *Trochammina inflata* and *Miliammina fusca*, while the lowest low-marsh is distinguished by the higher percentage of *Miliammina*. In the Oregon marsh samples, Jennings and Nelson (1992) do not indicate two low marsh subzones but this could be due to the lack of samples taken from the Oregon transect. It also must be noted here that generally the concentration of species in the low marsh is roughly half the concentration in the high marsh, thereby suggesting a higher sedimentation rate in the low marsh (Scott and Medioli, 1980b).

High percentages of *Miliammina fusca, Reophax nana, Ammotium salsum, Ammobaculites exiguus*, and sometimes a small number of calcareous species identify

Figure 2.2

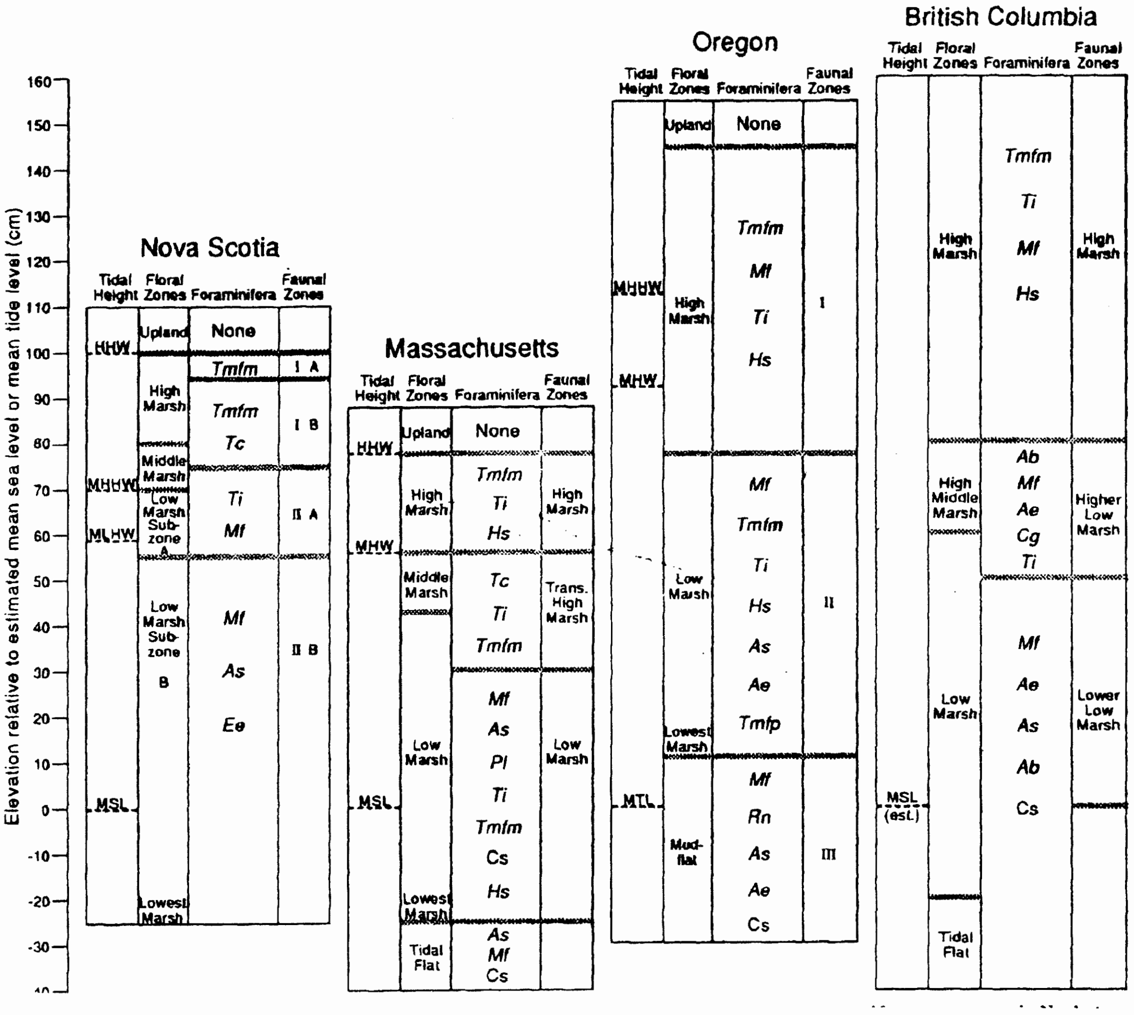


Figure 2.2.
Summary of tidal data, floral zones, foraminiferal assemblages, and faunal zones for four temperate coastal marsh areas.
Tmfm=Trochammina macrescens f. marcrescens, Tmfp=Trochammina macrescens f. polystoma, Ti=Trochammina inflata, Tc=Tiphotrocha comprimata, Mf=Miliammina fusca, Hs=Haplophragmoides sp., As=Ammotium salsum, Ae=Ammobaculites exiguus, Pl=Pseudothurammina limnetis, Rn=Reophax nana, Ab=Ammonia beccarii, Cg=Cribroephidium gunteri, Ee=Elphidium excavatum, Cs=calcareous and other estuarine species.
(Scott & Medioli, 1980a; Scott & Leckie, 1990; Williams, 1989; Patterson, 1990; Jennings & Nelson, 1992)

mudflats in Oregon. In contrast to previous studies, Jennings and Nelson (1992) were able to distinguish a separate mudflat faunal zone along the central Oregon coast because *Reophax nana* is restricted to the mudflat zone. In general they note that the position of floral zone boundaries relative to tide levels suggests that high marsh zones identified on the west coast of North America typically correspond with high, transitional high, and middle marsh zones on the east coast of North America (Jennings and Nelson, 1992).

In summary, Jennings and Nelson (1992) note that the vertical ranges of high and low marsh zones in Oregon limit the precision with which the size of submergence events can be estimated using foraminiferal assemblages. For example, a change from a high marsh assemblage to a mudflat assemblage could indicate submergence of 147 cm or as little as 37 cm. They conclude that their preliminary studies give evidence that there may be less potential for using foraminiferal assemblage zones to indicate small change in sea level on the west coast than on the east coast of North America. To remedy this problem in future studies, analysis should involve more detailed transect examination to identify subzones, more specifically narrow subzones, which can be widely recognized (Jennings and Nelson, 1992).

2.2 Alaska an observed mega-thrust earthquake

2.2.1 Microfossil analysis of the 1964 Alaska earthquake

In March 1964, coseismic subsidence, associated with the great Alaska earthquake, caused submergence of forest and tidal marshes in Turnagain Arm of Cook Inlet. The estimated maximum amount of coseismic subsidence was almost 2 m at Portage, Alaska. This decreased to the northwest along Turnagain Arm to ca. 1 m near Anchorage. Evidence of buried peats and "ghost forests" remains visible in the tidal marshes at Gridwood, Portage, and other locations around Turnagain Arm (figure 2.3) (Shennan et al., 1999).

Peat layers with sharp upper contacts with overlying clastic sediments (figure 2.4) characterize a marsh cliff section from Portage Flats, Alaska. These features can be compared to numerous sequences studied in the Pacific Northwest. The most spectacular difference between the Alaska event and others within the Pacific Northwest is that the other events have no direct observational records since the youngest coseismic submergence event is widely dated at ca. AD 1700. Therefore, because the timing of coseismic subsidence and post-seismic recovery at Gridwood Flats is precisely known (Plafker, 1969), we can use the paleoenvironmental information to evaluate similar sequences of coseismic submergence in the Pacific Northwest for events where no direct observation could be made, e.g. at Netarts Bay (Shennan et al., 1999).

The microfaunal evidence collected by Shennan et al. (1999) suggests four stages in relation to sea-level tendencies and relative sea-level movement. The first stage involves a period of negative sea-level tendency as fresh-water forest developed. This could represent a fall in relative sea-level or positive sedimentation buildup or a combination of both. This is caused by strain accumulation along the locked portion

Figure 2.3

Figure 2.3.
Photograph shows a garage that was upright prior to the Alaska 1964, 9.2 earthquake. In the background of the picture lies a 'ghost' forest. This forest died as a result of salt-water intrusion from the land subsiding prior to the earthquake.
-Photo by D. Scott, April 1997.

Figure 2.4

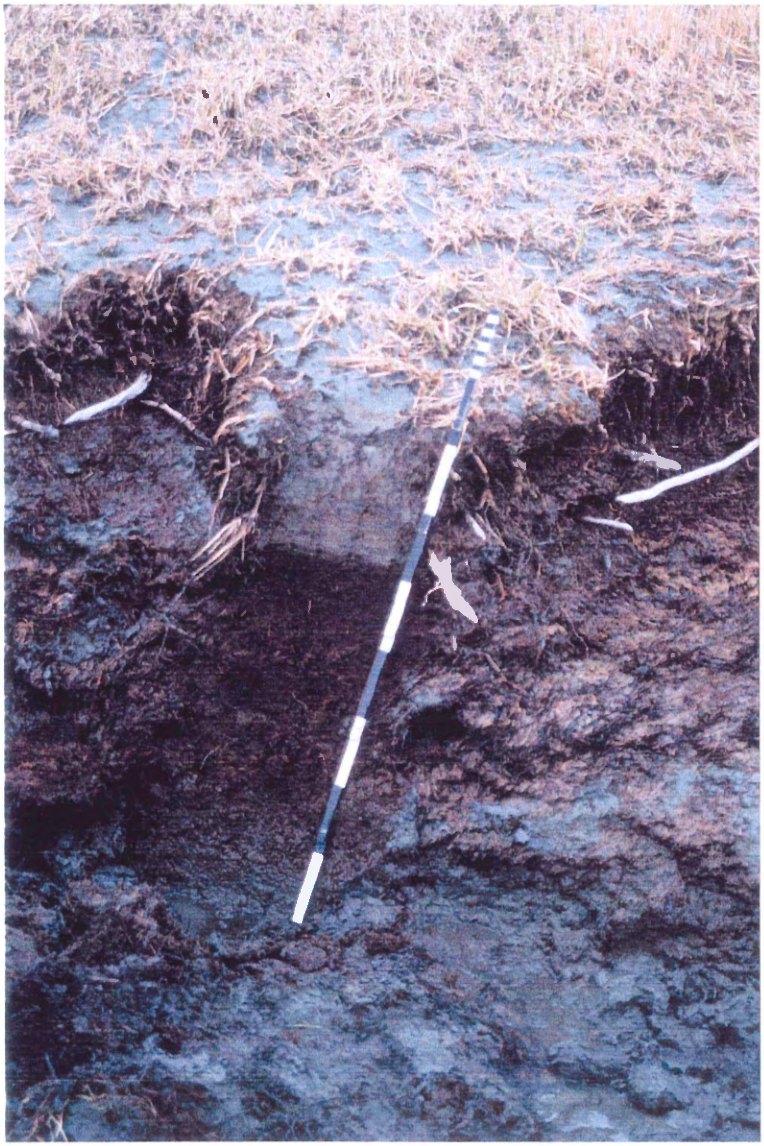


Figure 2.4.
Uplifted peat-mud couplet recording the 1964 Alaska mega-thrust earthquake. This area lies seaward of a "ghost forest". The stick has 10 cm intervals.
-Photo by D. Scott, April 1997.

Figure 2.5

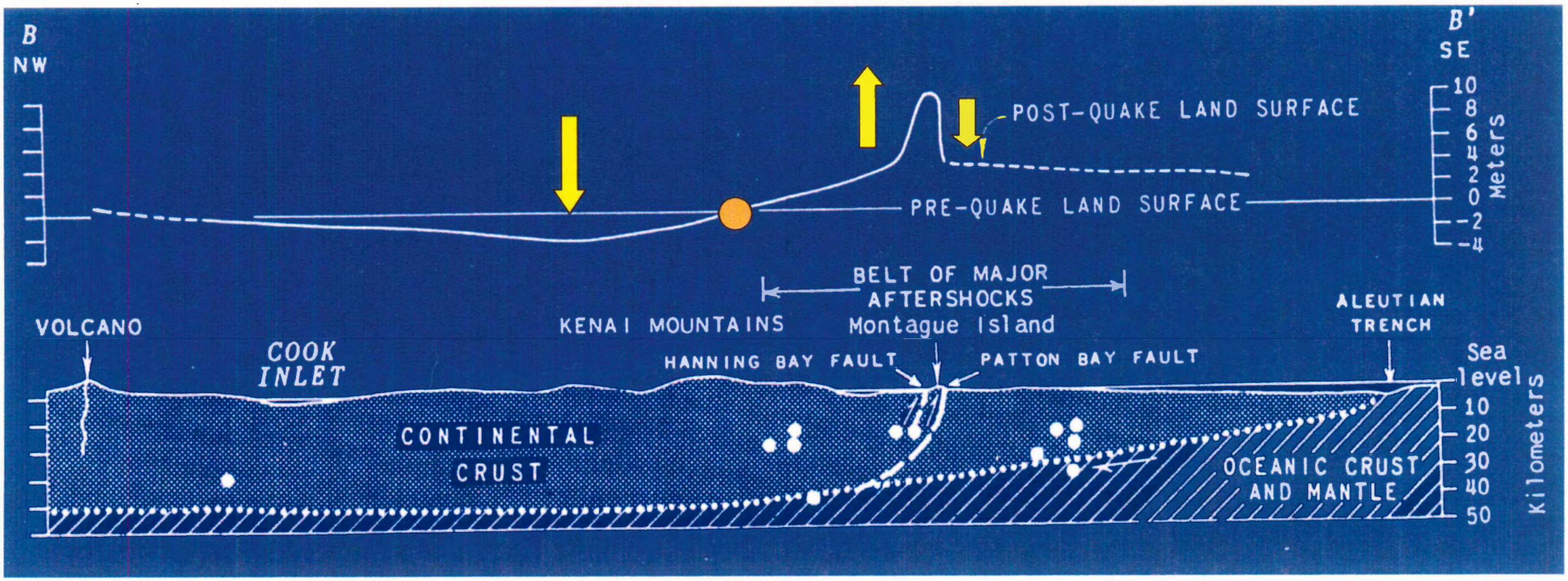


Figure 2.5.
Cross-section displaying relative land movement with respect to pre-earthquake land surface for the Alaska 1964 earthquake.
-modified from Plafker (1965)

↓	Land subsidence representing a pre-seismic rise in sea-level. (phase 2)
↑	Land uplift or negative sea-level tendency. (phase 4)
●	Area where there is no movement.

notable results came out of these studies: 1) earliest evidence of crustal plate convergence and associated large-scale thrust faulting in an arc type environment; 2) first demonstration of the direct relationship between coseismic vertical displacement of the sea floor and the generation of destructive tsunami; and, 3) earliest applications of studies now referred to as 'paleoseismology', to determine earthquake cyclicity (Plafker and Berg, 1994).

2.3 General Cascadian Earthquake Information

2.3.1 Geologic evidence of past great earthquakes

Atwater et al. (1995) reviewed Cascadian earthquakes and their potential effects in the Cascadian subduction zone. The main evidence for prehistoric earthquakes at the Cascadian convergent boundary consists of coastal strata indicative of sudden lowering of land (figure 2.6). These levels are often associated with tsunami deposits and less frequently with shaking (defined later in this summary). More than a dozen or so estuaries between Clayoquot Sound (British Columbia), and Eel River (California) record evidence of buried marsh or forest soils. The plant fossils and types of sediment indicate that the burial of many of these soils is the result of a 0.5-m sudden subsidence. This subsidence enabled tides to deposit mud on land that, prior to subsidence, was above the level of high tide (figure 2.7.a). The most recent uplift accompanied a 7.1 earthquake on April 25, 1992. The focus of the earthquake occurred at the boundary between the small Gorda plate and the North American plate (Oppenheimer et al., 1993). The earthquake raised approximately 25 km of the Cape Mendocino coast as much as 1.5 m (Atwater, 1997).

Many of the buried soils indicating sudden subsidence also show an abrupt upper contact with a sand layer suggesting instantaneous deposition of sand

Figure 2.6

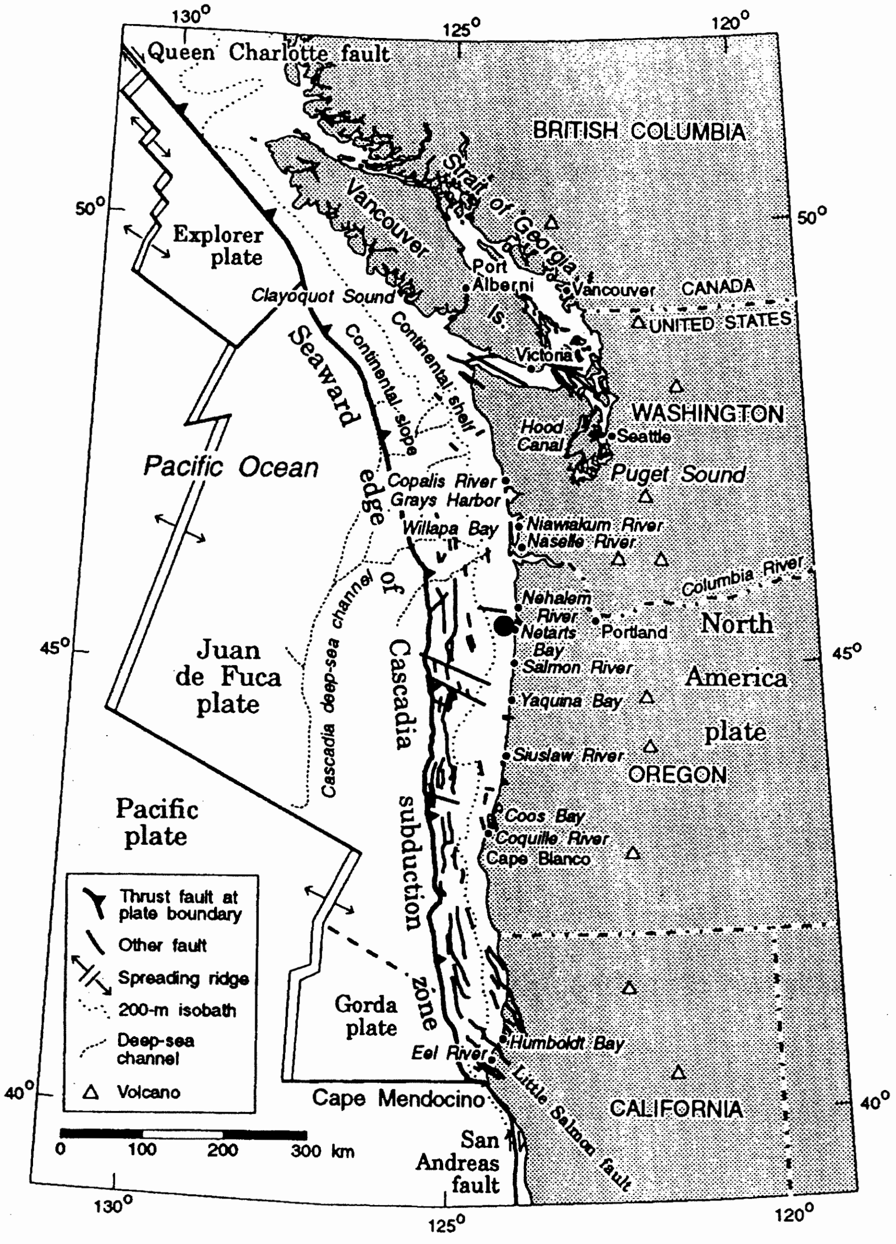


Figure 2.6.

Cascadian subduction zone showing place names, plate boundaries, and recently active faults within the North America plate. (afterAtwater et al., 1995)
● - represents location of this project, Netarts Bay.

characteristic of tsunamis (figure 2.7.b). Evidence of such sand layers can be found in British Columbia, Washington, and Oregon (also occurring in the core examined in this project) (Atwater et al., 1995). Seismic shaking producing liquefaction (figure 2.7.c) is evident in features less than 3000 years old near Vancouver (BC), (Clague et al., 1992), and at the Washington-Oregon border (Atwater, 1994).

The coast parallel to Washington and Oregon contains a number of shallow faults on which slip has occurred during the past 10000 years. Several Oregon estuaries that display evidence of sudden subsidence are located along eastward projections of these offshore shallow faults (Goldfinger et al., 1992; Atwater et al., 1995).

Recurrence intervals between successive earthquakes at several sites along the Cascadian subduction zone reveal intervals of hundreds to thousands of years but these estimated recurrence intervals are imprecise due to two problems. The first is that the number of earthquakes recorded in the geological record is not necessarily equal to the number of earthquakes that actually occurred. Over-estimation also plays a role where some buried soils are actually non-seismic events produced by breaching of tide-restricted bars, a change in the shape of the inlet, changes in sediment supply, and rapid sea-level rise. The second error that can occur when interpreting recurrence intervals is that of dating. This can include errors in radiocarbon analysis and converting radiocarbon ages into calendar years. This yields uncertainty (potentially of hundreds of years) in recurrence intervals for the Cascadian zone which are estimated between 400-600 years (Nelson and Personius, 1991; Atwater et al., 1995).

Figure 2.7

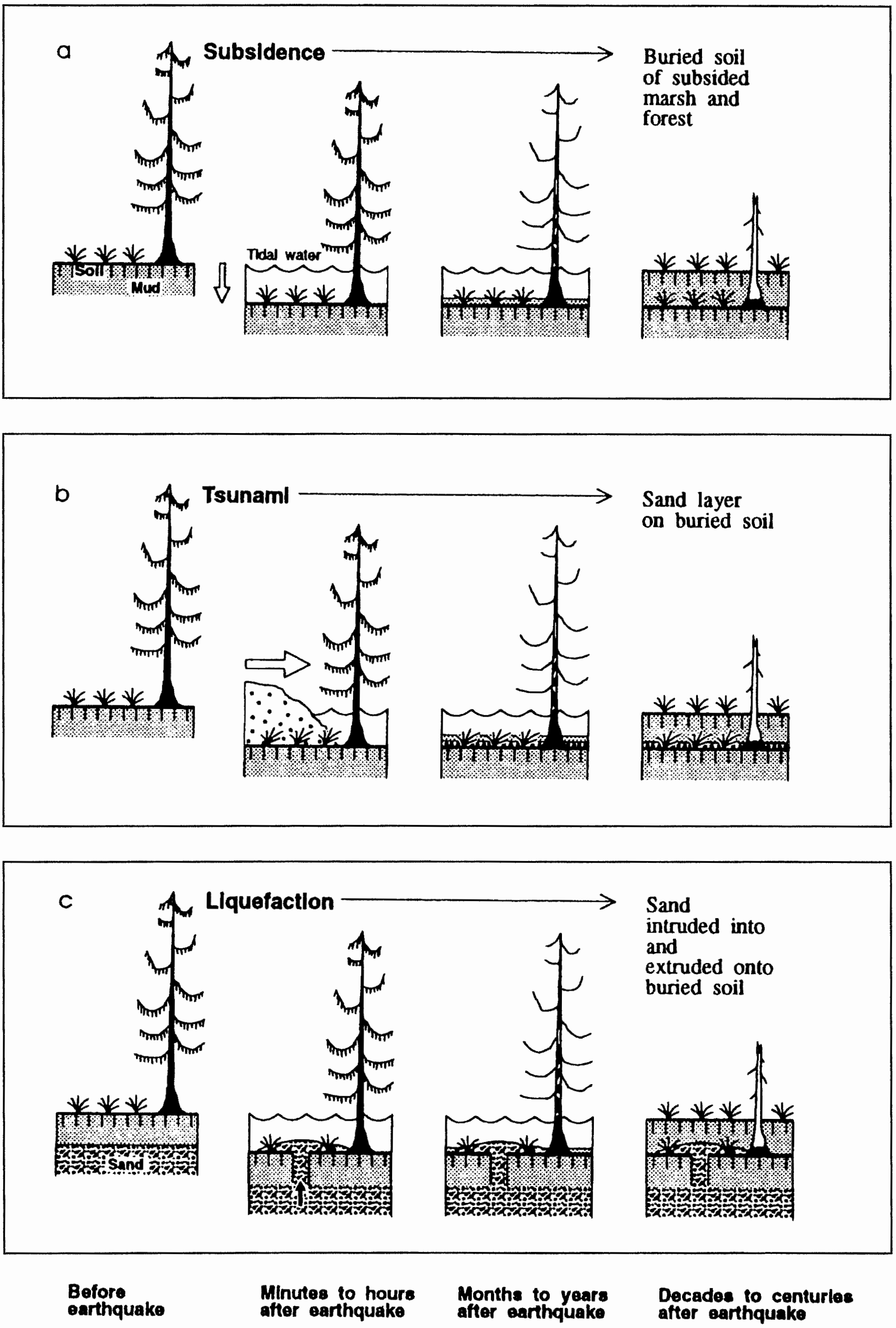


Figure 2.7.

a) Soil buried by tidal mud after earthquake-induced subsidence lowers land to intertidal zone.
b) Sand sheet deposited on a subsided soil by a tsunami that comes ashore minutes to hours after an earthquake.
c) Liquefied sand that erupted through and onto a subsided soil as a result of seismic shaking.

(after Atwater et al., 1995)

2.3.2 Earthquake history, Coos Bay, Oregon

Nelson et al. (1996) discussed the criteria for evaluating the size and rate of relative sea-level changes at Coos Bay estuary. They used evidence to infer a partial history of earthquakes over the past 4600 years in the area. The study also demonstrates the importance of detailed lithostratigraphic and biostratigraphic analyses when attempting to identify local, regional, seismic and nonseismic components of sudden and gradual submergence (Nelson et al., 1996).

The stratigraphic sequences at Winchester Creek (the sample site within Coos Bay) consist largely of peat-mud couplets, where the mud gradually grades upward into peat which is then abruptly overlain by muds of the next couplet. Of these ten sharp couplets, only two (4 and 5) show site-wide lateral extent and abrupt changes in lithology and microfaunal assemblage, indicative of sudden subsidence. Nelson et al. (1996) inferred coseismic subsidence for contacts 1, 4 and 5 because submergence was likely too large to be caused by changes in river shape or breaching sandbars. They reason that this sudden subsidence could have been the result of slip on shallow local faults or from regional flexure of the North American plate during a great subduction boundary earthquake. The other couplets display one of either seismic or nonseismic subsidence, because the subsidence in these couplets is < 0.5 m (Nelson et al., 1996).

From sampling within Winchester Creek, Nelson et al. (1996) inferred that large-scale earthquakes occurred at 300, 1700, and 2300 years ago. They also note that evidence for coseismic subsidence involves changes in the fossil assemblage displaying sudden submergence of more than a metre, sand sheets deposited by tsunamis, and liquefaction features. The study at Winchester Creek shows that reconstruction of great earthquake history for the Cascadian subduction zone will require thorough litho- and biostratigraphic studies of several sequences of peat-mud couplets in estuaries throughout the west coast of North America (Nelson et al., 1996).

Chapter Three: Methods

3.1 Core collection

The 'Pacific Rim Project' (J. Lipps, University California at Berkeley and D. Scott, Dalhousie University) collected a vibracore in November 1999, which was three meters in length, from Netarts Bay salt marsh, Oregon. The vibracore allows for deep penetration into soft sediment with little compaction. A vibracore consists of an upright aluminum pipe to which a vice is clamped; the vice attaches the pipe to a motor on the ground. The motor provides an extreme amount of vibration that, with a little guidance, propels the aluminum pipe into the ground (Figure 3.1). Once the vibracore is no longer gaining depth, the aluminum pipe is severed near the ground and the ends sealed. The seal provides suction as the pipe is lifted out of the ground so as to ensure that the core does not slip out of the bottom. After the pipe was removed from the ground, the bottom end was capped, taped and labeled, with up direction noted with an arrow on the side of the pipe. The core was then transported to the University of California at Berkeley where it was split in half along its length with a circular saw. One half was kept complete and used for stratigraphic reference and resampling, if necessary. From the other half, 10cc samples were taken every centimeter, then put into plastic sample bags and sent to Dalhousie University.

3.2 Processing

This core was selected because of its high marsh location where probable precursor earthquake events were found previously (Shennan et al., 1998b). The 10cc core samples were removed from the sample bags for processing through >500μm, >63μm, and finally <63μm->45μm sieves (figure 3.2). Using only one >125μm sieve can result in loss of up to 99% of the fauna (e.g., Schrøder et al., 1987).

Figure 3.1

Figure 3.1.
Vibracore set up. To the left is a tripod used for retrieving the core. On the right is the aluminum pipe, which will hold the core, once in the ground.
-Photo taken from Dalhousie University southeastern United States Honors field trip, September 2000.

The use of the >63μm and <63μm to >45μm sieve has been found to isolate foraminifera and thecamoebians. Each 10cc sample is washed through the stack of sieves (largest to smallest), where the greater than 500μm material is discarded. The sieves containing the material smaller than 500μm to 63μm and smaller then 63μm to 45μm are placed into previously labeled sample cups. Alcohol is then added to each sample cup in the last stage of processing and inhibits the deterioration of microfossils and the growth of bacteria.

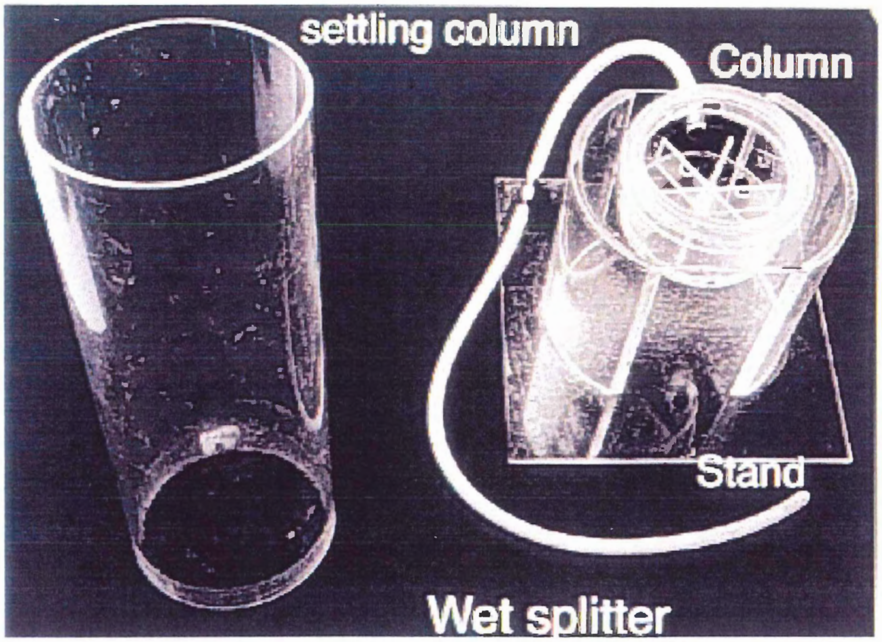
3.3 Examination

Examination of species abundance and diversity generally requires the sample to be partitioned in a wet splitter that divides samples into equal parts to reduce the counting load and increase visibility, thereby improving accuracy. Wet splitters come in a number of configurations; divisions of 1/4th, 1/6th, or 1/8th (Scott and Hermelin, 1993; Scott et al., 2001). For the purpose of examination throughout this project a 1/8th wet split was used (figure 3.2).

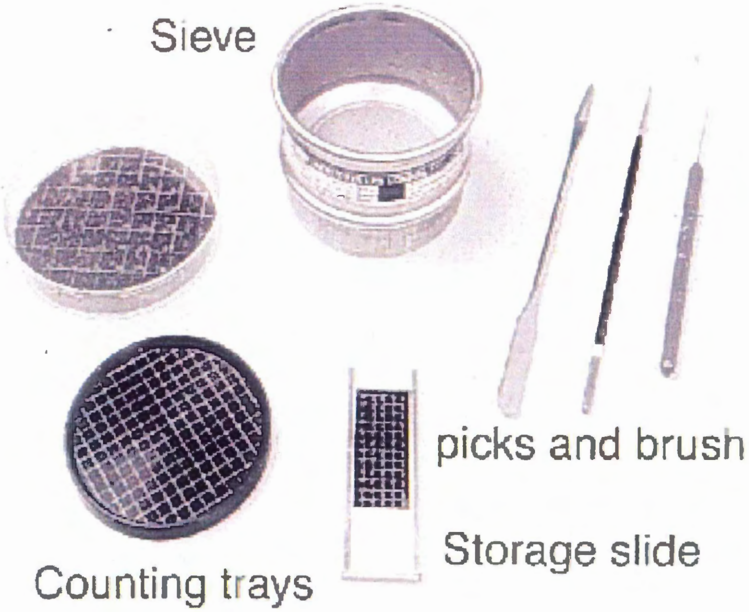
The wet splitter also provides a means of dilution for organic matter, which can become quite cumbersome during counting because of its tendency to mat. The wet splitter is a cylinder ca. 50 cm long, which seals onto a shorter cylinder of the same diameter that holds eight pie sections and one drainage hose (figure 3.2). The sample is poured into the cylinder, which is full of water, and left to settle for approximately one hour. The water is then released through the drainage hose that lies above the settled samples. At the base of each pie piece is a rubber-stopper where an 8th of the sample can be retrieved for examination.

The 8th of the sample is drained into a petri dish, which has been divided into 1 cm squares across its base (figure 3.2). The sample is then counted systematically by row or column to preserve accuracy. A count of at least 300 specimens is

Figure 3.2



The above wet splitter is used to divide a sample into equal parts, configurations of ¼, 1/6, or 1/8. (Scott et al., 2001)



The above devices are used to ease the counting process. Sieves separate material of different sizes, counting trays allow the counter to keep track, picks and brushes are used to move the material around.
(after Scott et al., 2001)

recommended to ensure accountability and accuracy (Murray, 1973). The samples in the petri dish are observed under microscope at 20 or 40x magnification. The aid of a counting device also proves useful when a number of different species are present in the sample.

3.4 Photography and Scanning Electron Microscope

Before the core was sampled at Berkeley, the core was photographed and scanned into digital format and saved onto a compact disk, which was sent to Dalhousie University. Representative photographs of selected foraminifera are included here from a photo bank of D.B. Scott. The foraminifera are scanning light microphotographs and the thecamoebians are scanning electron micrographs.

3.5 Identification

Due to the diversity of foraminifera and thecamoebians, identification during counting was assisted by a number of photographic plates, textbooks, and papers for reference, as well as first hand inquiry to the thesis supervisor. A previous course in micropaleontology assisted with identification, interpretation and lab preparation.

3.6 Data Presentation

Data tables were compiled in Microsoft Excel (spreadsheet) and include sample number (which is also depth in this case), total number of species, total number of individuals, and individual species in alphabetical order. Total number of species and individuals are raw numbers and actual species numbers are presented as a percentage of the total number of individuals per 10cc sample. The table was then saved as a text file and imported into Cricket-Graph (MacIntosh program) for plotting to illustrate variability with depth in core. The graphs were then imported into Adobe Illustrator® and detailed for final presentation.

Raw data tables allow for reader to make interpretations while graphing provides easy understanding of the author's findings. Data tables are presented in Appendix A, while graphs are presented in chapter 4.

Chapter 4: Results

4.1 Background Carbon 14 dating

Previous calibrated radiocarbon dates were provided in Shennan et al. (1998b) from the calibration method produced by Stuiver and Reimer (1993). Core 18 from the Shennan et al. (1998b) study, which shows calibration dating of near bottom and top transitions, was collected from a high marsh zone similar to the core examined for this study (the two sites are approximately within 20 m of each other). Therefore, through stratigraphy and the number of transition zones present in the cores, I was able to correlate transition 1 as being approximately 300 years old (1700 A.D.), occurring between 102-130 cm depth; transition 2 between 131-161 cm depth is dated at ca. 1670 +/- 60 years; transition 3 between 167-203 cm depth dated at approximately 1840 +/- 60 years; and transition 4 correlated with the bottom event of core 18 occurring between 260-290 centimetres (approximately 3000 years before present) (figure 4.1).

4.2 Stratigraphy of core

The stratigraphy of the core tends to follow a repetitive peat-sand-tidal mud sequence. The peat is generally reddish-brown and contains organic material. The sand layers vary from 1 to 12 cm and are composed of fine grained minerogenic material, dominantly quartz grains, that lie unconformably over the underlying peat layer (perhaps a type of instantaneous erosion). The tidal flat mud is fine-grained, grey clay lying conformably over the sand layer (figure 4.1).

Figure 4.1.

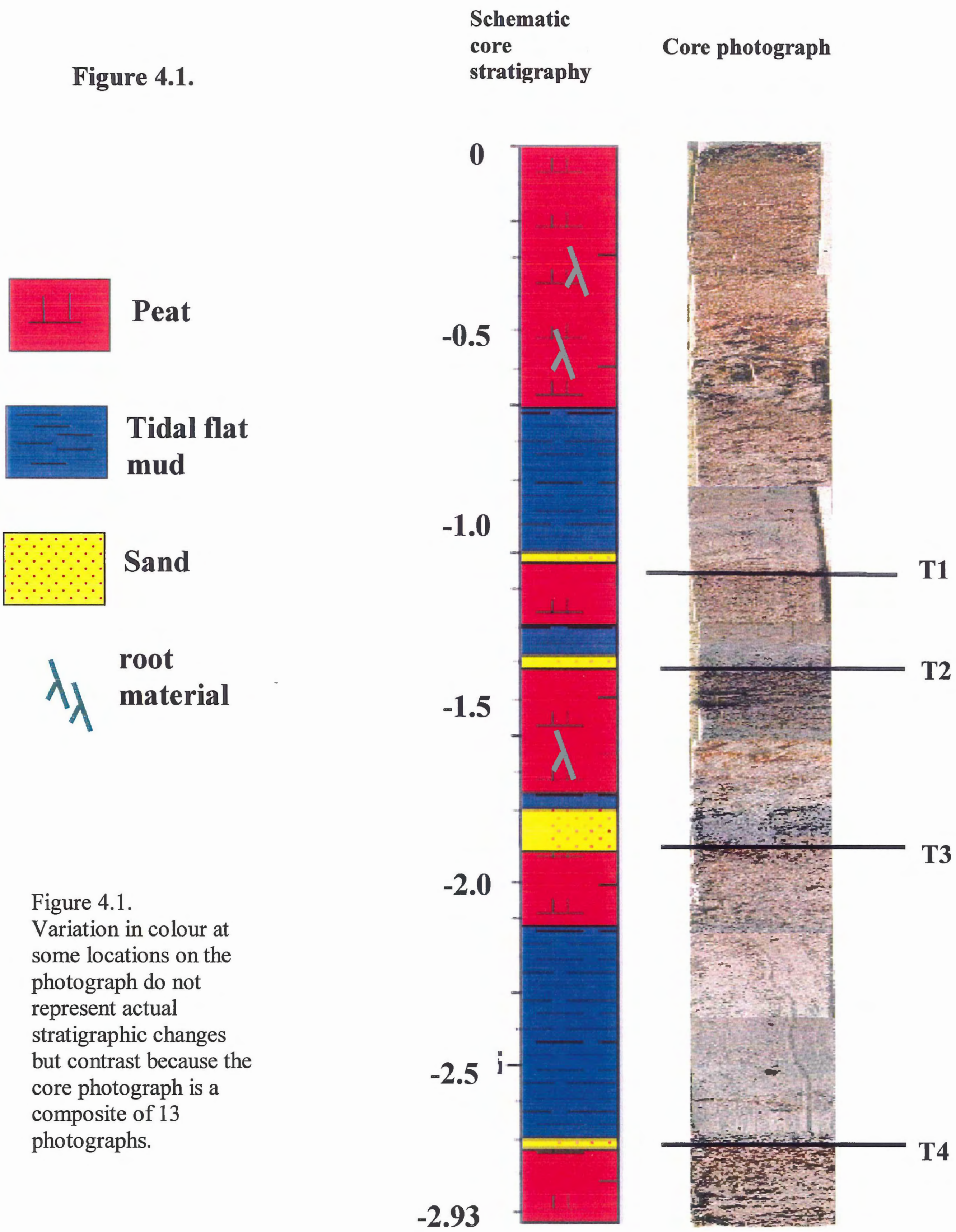


Figure 4.1.
Variation in colour at some locations on the photograph do not represent actual stratigraphic changes but contrast because the core photograph is a composite of 13 photographs.

Table 4.1

Marsh Zones	**Foraminifera**	**Thecamoebians**
High marsh **upper** **lower**	• ***Haplophragmoides wilberti*** • ***Tiphotrocha comprimata*** • ***Trochammina macrescens f. macrescens*** • ***Trochammina inflata***	• ***Centropyxis aculeata*** • ***Centropyxis constricta*** • ***Cucurbitella tricyspis*** • ***Heleopera sphagni***
Mid marsh	• ***Trochammina inflata*** • ***Trochammina macrescens f. macrescens*** • ***Arenoparella mexicana*** • ***Miliammina fusca***	
Low marsh	• ***Miliammina fusca*** • ***Trochammina macrescens f. polystoma***	

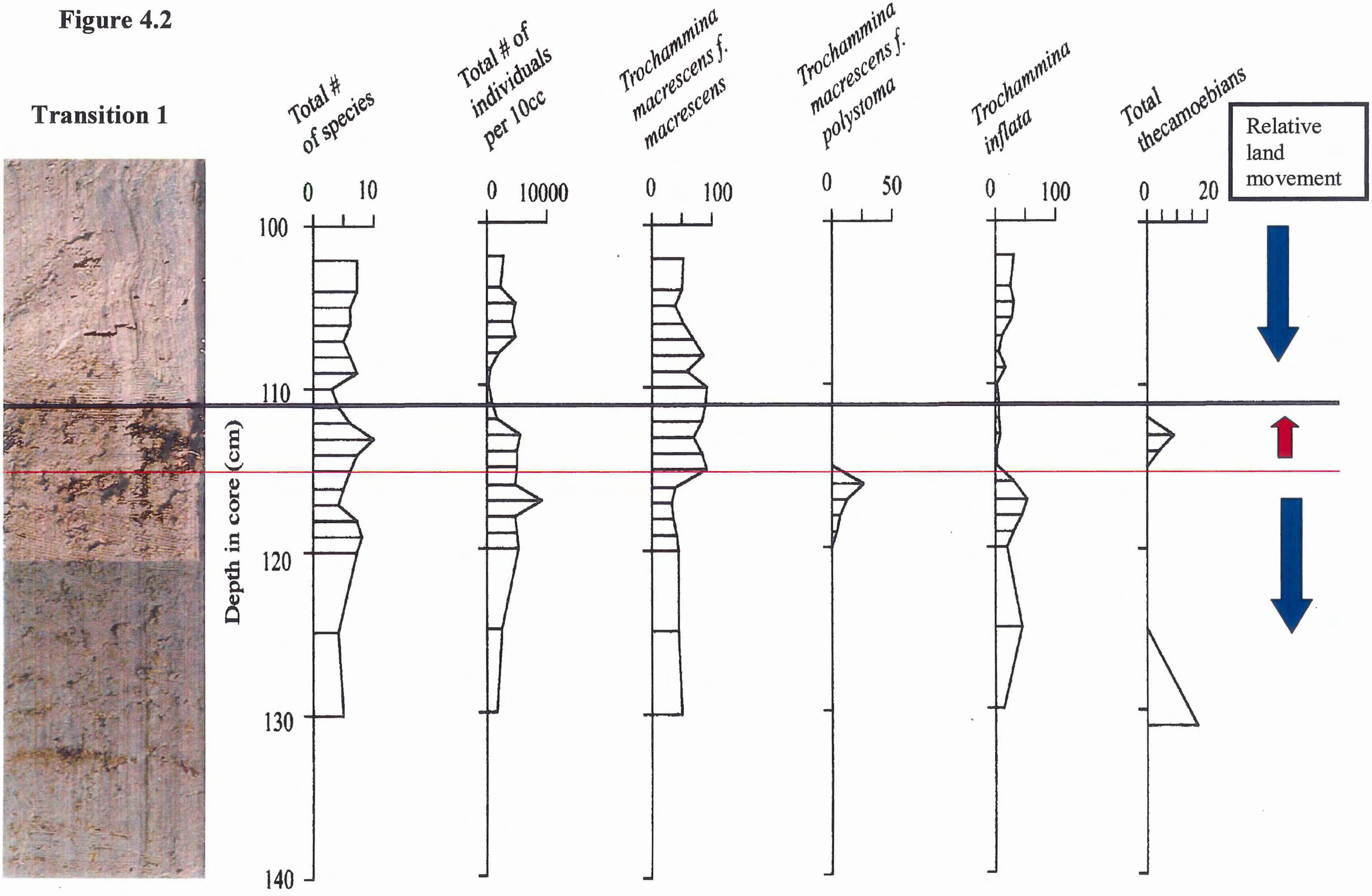
Table 4.1.
Foraminiferal and thecamoebian species found in this study and their representative zones in Netarts Bay, Oregon. Note that unlike table 2.1 and table 2.2 I have interpreted a subzone within the high marsh zone where, *Haplophragmoides wilberti* represents the upper high marsh and *Trochammina inflata* reflects lower high marsh and mid-marsh.

Figure 4.2-4.5

Figures 4.2 to 4.5 (transitions 1-4) show a photo of the transition (to the left) with a thick dark line across the graphs representing the abrupt boundary between peat and the overlying tsunami deposits. The species graphed are those which indicate a precursor event prior to the earthquake denoted by the thinner red line. Arrows represent the relative land/sea-level movement (uplift or submergence) occurring prior, during and post-quake.

Figure 4.2

Transition 1



Transition 2: Transition 2 lies between 161 and 131 cm (figure 4.3). At 161 cm a very high abundance of partly decomposed organics passes upward into a marsh peat to about 142 cm. From 142 cm to 134 cm is a "tsunami layer" with a large quantity of sand particles. Intertidal muds are up section from the tsunami deposit until 133 cm. The end of transition 2 from 133 to 131 cm we return to a high marsh.

Trends in transition 2 reflect a decrease in total number of species and total number of individuals at 141 cm. Note the increase in *Trochammina inflata* at 143 cm and a total dying off of *Haplophragmoides wilberti* at 141 cm. A large drop in elevation is inferred from a lithological change just above the peat.

Transition 3: Transition 3 covers the core section from 203 to 167 cm (figure 4.4). At 203 cm marsh peat is present and increases in organic content until roughly cut off by a thick tsunami layer at 192 cm. The tsunami layer extends from 192 cm to 180 cm. Above the tsunami layer intertidal sediments occur from 180 cm to 176 cm. Up-core from the intertidal deposits is an abrupt change to high marsh with abundant organic material displaying little decomposition.

The main microfossil trend in transition 3 is the pronounced decrease or dying off of species and total numbers of individuals from 188 cm to 181 cm, approximating the inferred tsunami layer. The exception here is the slight increase in *Trochammina inflata* after a general decrease of the other species including a drop in *Haplophragmoides wilberti* just below the transition zone, similar to that in transition 2. This section can be interpreted as going from high/brackish down to the middle part of high marsh then back up to high-brackish marsh following the tsunami event representing a substantial drop in elevation.

Figure 4.3

Transition 2

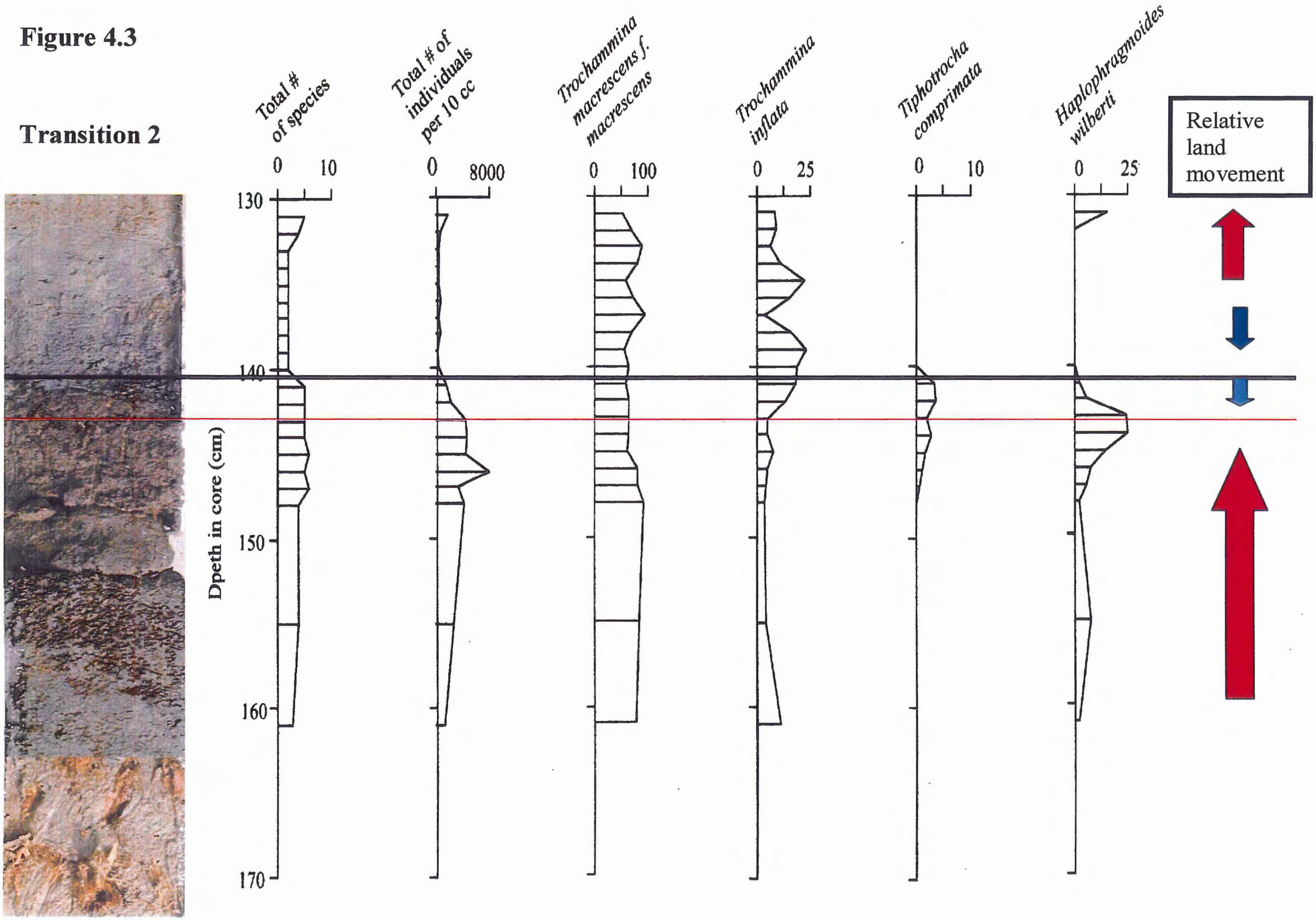
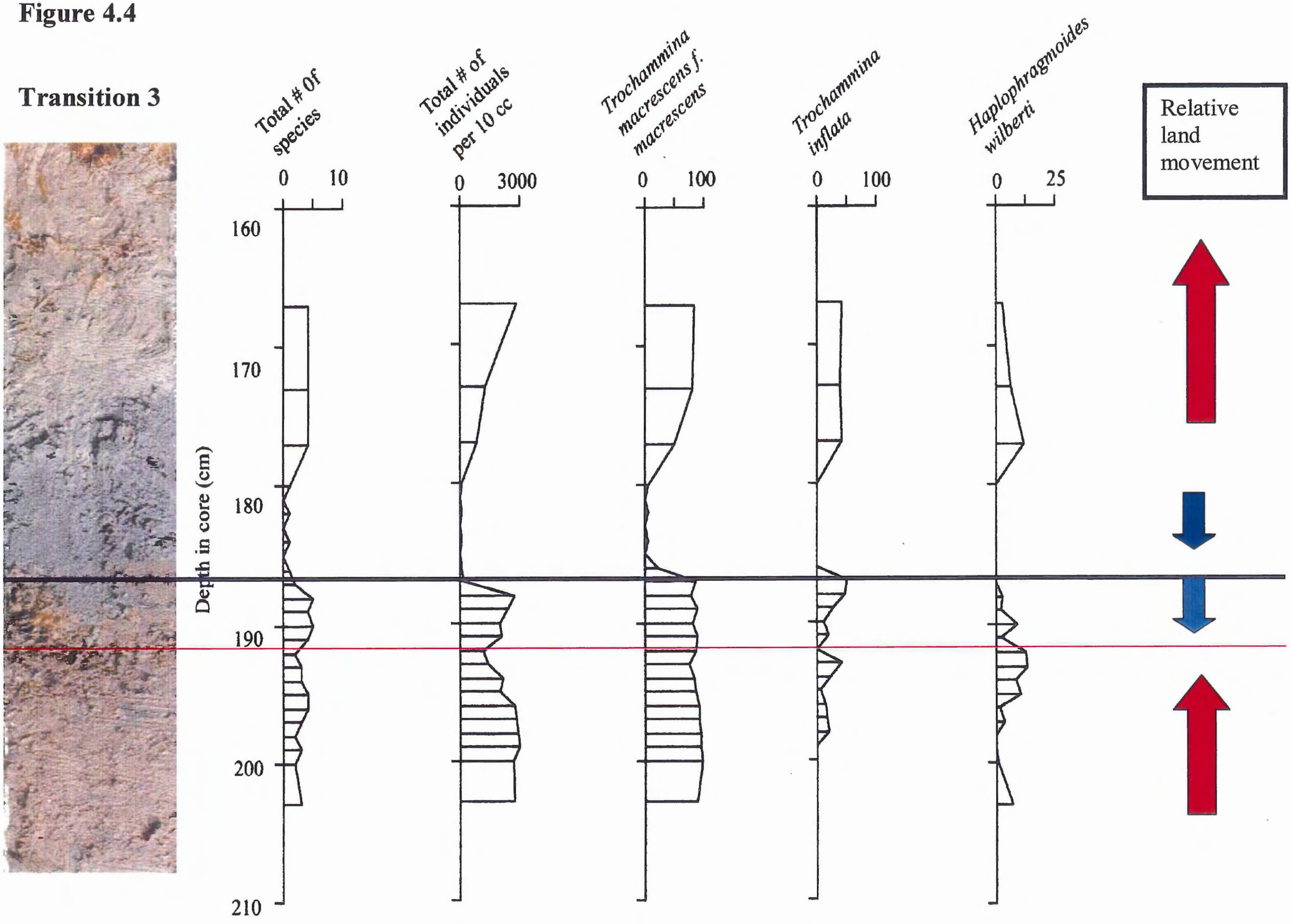


Figure 4.4

Transition 3



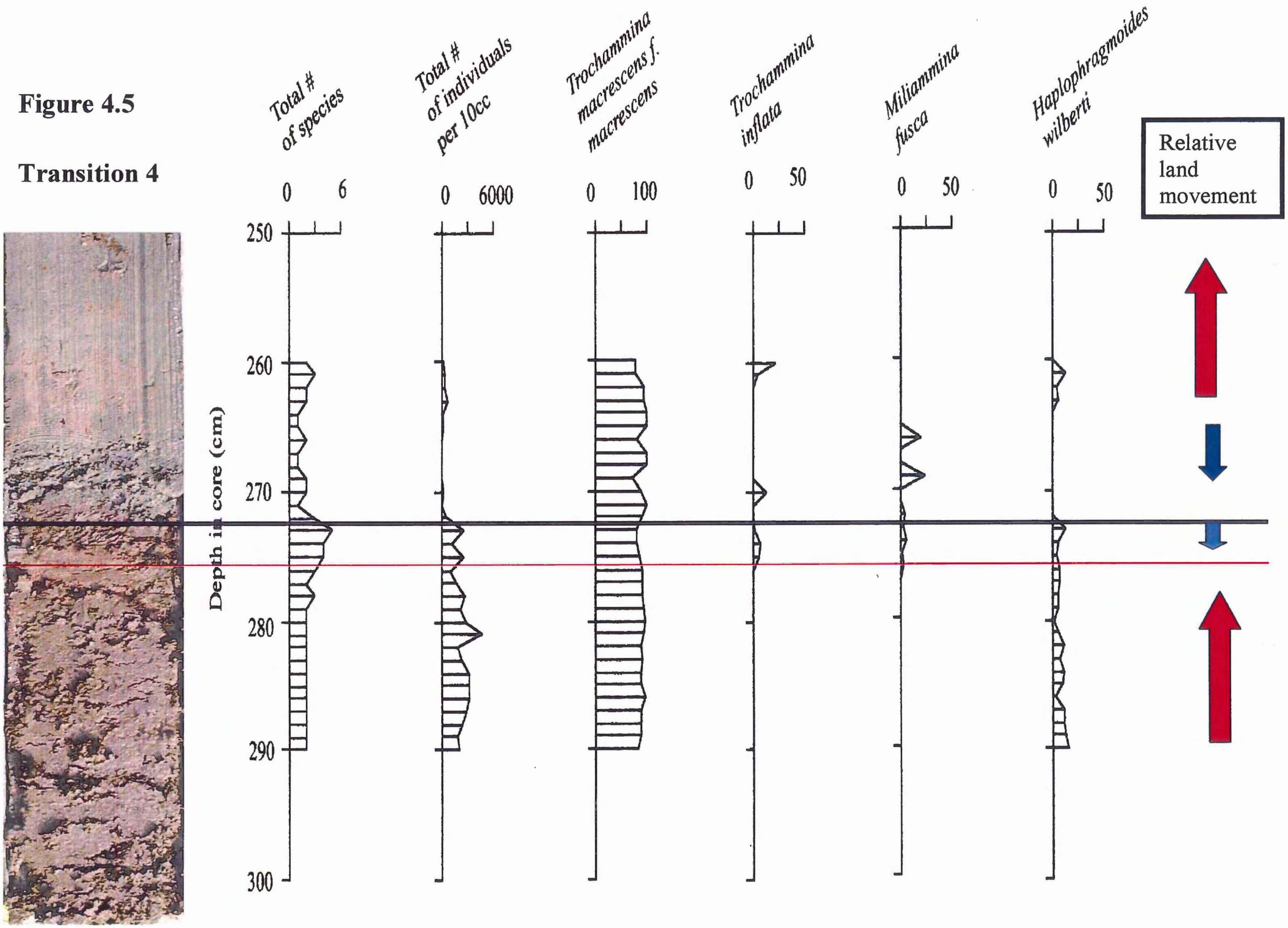
Transition 4: Transition 4 runs from 290 cm to 260 cm (figure 4.5). At 290 cm, there is marsh peat to 273 cm where a tsunami layer is present from 273 to 270 cm. The rest of the core above reveals intertidal mudflat deposits to 260 cm.

The trends of this section show a strong decrease at 273 cm in total species and individuals as well as in *Haplophragmoides wilberti,* at the base of the tsunami deposit. Prior to this a small increase in *Trochammina inflata* and *Miliammina fusca* indicates a transition from, just prior to the tsunami layer, an original high-brackish marsh zone to a middle-high marsh zone. Can also note here that just before the tsunami layer there is a large drop in elevation.

Although each transition, from 1-4, shows different trends, the following discussion chapter explains what those differences represent in terms of earthquake precursor events.

Figure 4.5

Transition 4



Chapter five: Discussion

5.1 Intra-core comparison

In the previous chapter the dominant changes were evaluated in each transition with respect to species and environmental zonation changes (e.g. high, mid, or low marsh). Here the four transitions are evaluated together to determine overall trends. These trends may later be applied as a general theory for earthquake precursor events.

Because we are concerned with precursor events we will focus the trends around the transition and precursor lines (black and red line through the graphs in the previous chapter, fig.4.2-4.5). With this in mind transition 1 is clearly different from transitions 2-4 (table 5.1). This is shown by the appearance of thecamoebians just before the transition line in transition 1 at 113-114 cm, representing an overall uplifting prior to the transition. Transitions 2-4 show the opposite trend by displaying subsidence prior to the transition. There is no obvious tsunami layer in transition 1.

Three of the transitions have a characteristic decrease in total number of species and total number of individuals in the tsunami layer (directly above the transition line). Each of the four transition zones also display a change in marsh environment, uplift in transition 1 and subsidence in transitions 2-4, just before the inferred seismic event. Prior to this change in marsh environment, the environments had been steady for some time. It can also be noted that storm and barrier breach events should not be associated with a change in vertical land movement relative to sea-level. Although, this does not concern precursor events, it is important for identifying tsunami layers that are not related to land movement but from earthquakes in other tectonically active areas. We note here that the difference between tsunami layers and storm layers or barrier breach layers is grain size and presence or absence of microorganisms. Tsunami layers have very fine grain size while storm and barrier

Table 5.1

Youngest ↑ Oldest

	Transition 1			Transition 2			Transition 3			Transition 4		
	Land	Zonation	Species	Land	Zonation	Species	Land	Zonation	Species	Land	Zonation	Species
Post-quake	↓	mid-marsh	*inflata*	↑	lower high-marsh	*inflata* *macrescens*	↑	middle high-marsh	*haplo* *inflata*	↑	lower high-marsh	*inflata* *haplo* *fusca*
Tsunami deposit	○	○ ○	○ ○	↓ 🟨	🟨	🟨	↓ 🟨	🟨	🟨	↓ 🟨	🟨	🟨
Precursor	↑	Brackish	*thecs*	↓	mid-marsh	*inflata* *comprimata*	↓	mid-marsh	*inflata* *macrescens*	↓	mid-marsh	*inflata* *fusca*
Pre-quake	↓	low marsh	*polystoma*	↑	high marsh	*haplo*	↑	high-marsh	*haplo* *macrescens*	↑	high-marsh	*haplo*

Table 5.1. Summary of transition zones with respect to land movement, marsh zonation, and indicator species.

Post-quake = event after earthquake
Tsunami deposit = minerogenic material deposited just after earthquake
Precursor = event just prior to earthquake, few centimetres before
Pre-quake = stable marsh environment prior to precursor event
Inflata = Trochammina inflata, thecs = thecamoebians, polytoma = Trochammina macrescens f. polystoma, Macrescens = Trochammina macrescens f. macrescens, comprimata = Tiphotrocha comprimata, haplo = Haplophragmoides wilberti, fusca = Miliammina fusca.

↓ subsidence ↑ uplift ○ ○ sandy layer 🟨 tsunami layer breach events have larger more coarse grains (Clague and Bobrowsky, 1994a, b). Tsunami layers are distinct, containing a few to no microorganisms' (Scott, unpublished results from Papua NewGuinea Tsunami, 1997) while storm and barrier breaches often contain more organic material (Collins and Scott, 1999).

Transition 2, 3 and 4 display similar trends. The general trend is a small subsidence precursor event involving the decrease of *Haplophragmoides wilberti*, just prior to or at the transition lines, followed by an increase in *Trochammina inflata* at and above the transition lines. The decrease in *Haplophragmoides wilberti* not only signals a small drop in elevation, but a higher salinity which would result from more marine influence (e.g. drop in elevation). This trend is strongly evident for transition 2 and 3. Transition 4 shows a similar, yet weaker trend compared to transition 2 and 3. Therefore, we can define a strong association between transition 2 and 3 and a precursor earthquake event. Although, transition 4 displays weak evidence for a precursor event this could be the result of the tsunami layer displacing the top centimetres upon deposition (a type of instantaneous erosion).

5.2 A comparison with diatom and pollen results from Netarts Bay, Oregon

> "Stratigraphic investigations of the intertidal sediments at Netarts Bay, Oregon, using lithological, pollen and diatom analyses reveal different types of submergence associated with peat-mud couplets during the last 3500yr. Three peat-mud couplets record gradual sedimentation changes within an infilling body of water. Four other couplets record rapid submergence, burial of tidal marshes and their replacement by low marsh environments. In three of the events rapid submergence is small 0-0.5 m. The most recent marsh subsidence event, around AD 1700, was 0.4 +/- 0.3 m. Most of the buried peats contain microfossil evidence for gradual increase in marine influence before the rapid change from organic to minerogenic sedimentation" (Shennan et al., 1998b, p. 365).

Transitions 2-4 displayed events similar to the rapid submergence noted in Shennan et al. (1998b), recorded as a small slower submergence (compared to the earthquake itself), burial of high marsh and replacement by middle/low marsh environments. In contrast, transition 1 displays the opposite event recorded as a small uplift of low marsh replaced by brackish/high marsh environments. The amount of emergence/uplift in all four transitions is inferred to be small, between 0.1-0.7 m based on elevation zones determined from marsh foraminiferal assemblages (Scott and Medioli, 1980a; Jennings and Nelson, 1992; Scott et al, 1996). As for the cause of transition 1, it may or may not be related to a seismic event.

5.3 A comparison with historically documented record from Alaska

Shennan et al. (1999) observed four phases of relative land and sea-level changes post and prior to the Alaska, March 1964, 9.2 magnitude, mega-thrust earthquake. They are as follows:

> "The first phase is the development of freshwater swamp above high marsh sediments during relative land uplift, caused by strain accumulation along the locked portion of the Alaska-Aleutian subduction zone. In second phase, the top 2 cm of the peat, all microfossil groups record pre-seismic relative sea-level rise (relative to land subsidence). The third phase is rapid land subsidence, 1.7 m, during the earthquake of March 1964 that initiated intertidal silt accumulation above the peat. The final phase is the colonisation

> of mudflats by salt marsh communities during post-seismic land uplift." (figure 5.1) (Shennan et al., 1999, p.55).

If we apply the Alaska model to transitions 1-4, we can see that transitions 2-4 follow a very similar pattern while transition 1 does the opposite. In transitions 2-4, at the base of the transition sequence a high marsh/brackish environment is indicated by the *Haplophragmoides wilberti* (phase 1). The top few centimetres of the peat record a pre-seismic relative sea-level rise (relative to land subsidence) indicated by the increase in *Trochammina inflata* and decrease in *Haplophragmoides wilberti* (phase 2). The third phase involves between 0.1 and 0.7 m of rapid land subsidence initiating the accumulation of intertidal mud overlying the peat (phase 3). In this phase we also see the instantaneous deposition of tsunami minerogenic material between the peat and overlying intertidal sediment; these layers varied from 1-12 cm thick. The final phase involves the development of middle to high marsh over the mudflats during post-seismic uplift (relaxation), indicated by the return of *Haplophragmoides wilberti*.

In transition 1, phase one is represented by the development of a low-middle marsh environment over a high/brackish marsh environment, evident by the dying out of thecamoebians and the increase in *Trochammina inflata* and *Trochammina macrescens f. polystoma*. A re-emergence of thecamoebians in the top 4 cm of the peat layer indicates pre-seismic lowering of relative sea-level caused by land uplift (phase 2). Phase 3 represents land uplift of less than 0.2 m that could be non-seismic and is not necessarily linked to a mega-thrust earthquake. The final phase, occurring during post-seismic land subsidence, is the colonisation of high marsh species over the 1-cm sand layer, which overlies the brackish environment. It is also possible this sequence represents a simple sedimentation cycle where no uplift is required, simply infilling.

Figure 5.1

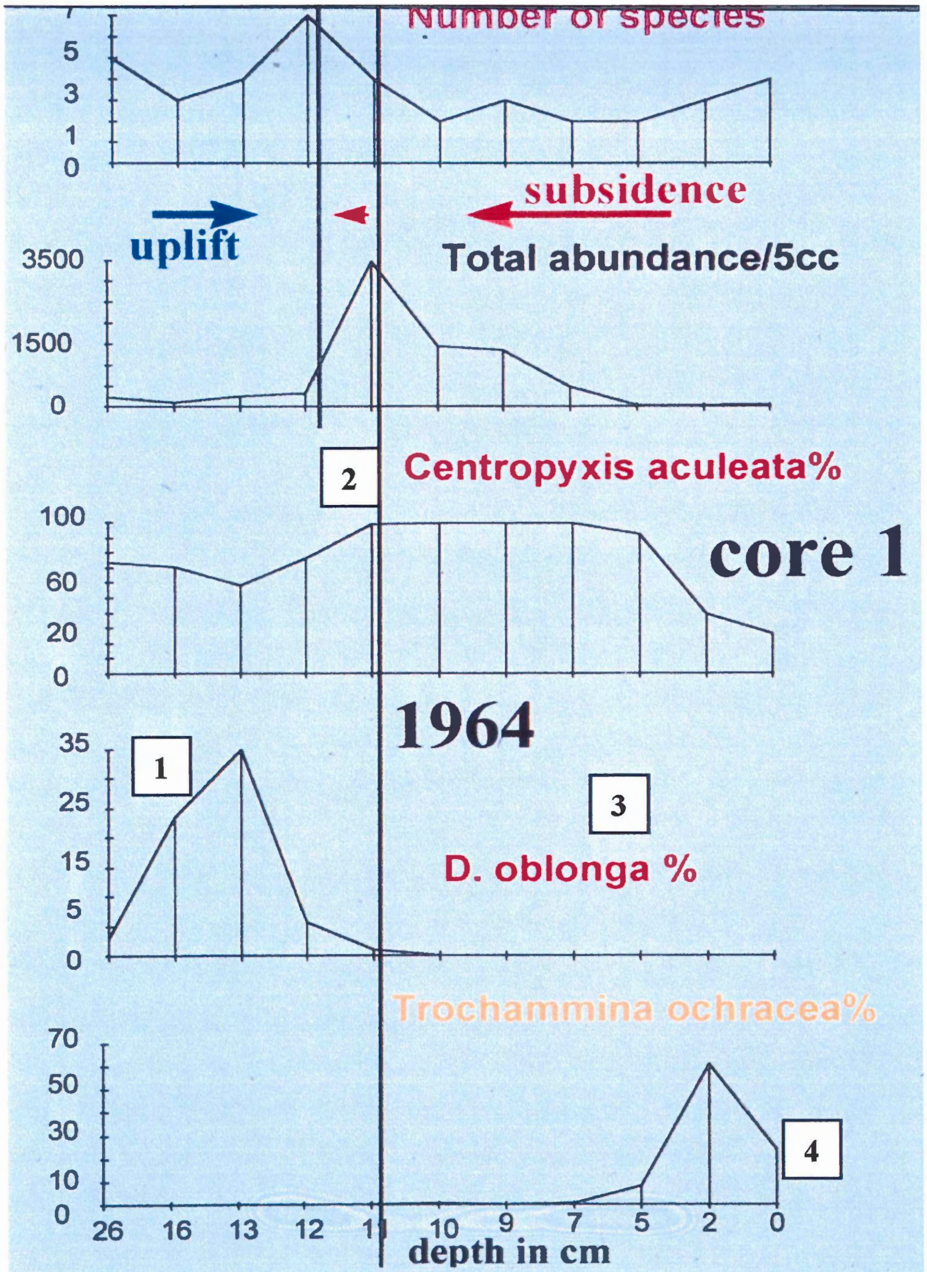


Figure 5.1.
Phase 1 – fresh water swamp above high marsh during a relative uplift.
Phase 2 – Top cm of peat (11th cm) reflect pre-seismic relative sea-level rise.
Phase 3 – rapid land subsidence of 1.7 m.
Phase 4 – colonization of mudflat species during post-seismic uplift.
(after Shennan et al., 1999)

The Alaska earthquake provides a documented, historical record, which enables us to apply this four-phase theory to other areas where no historic records exist for mega-thrust earthquakes. If this four-phase theory fits the phases that occur in other areas we can infer that a similar event has occurred. The value of the Alaska earthquake is that it provides the small scale timing that is not possible to obtain from pre-historic earthquakes. Radiocarbon dating error (+/- 100 years) is far greater than the time frame we want to establish.

5.4 Importance of physical environment to the precursor possibility

An important self-limiting aspect of this precursor event theory is the necessity to have a core from an area that would display changes in foraminiferal/thecamoebian assemblages with subsidence/uplift. For example, in a core from upper low-marsh, which subsided ca. 0.5 m to an area of lower low-marsh, the subsidence may not be detected by a change in assemblages because this area does not have an assemblage change in that range. This is why areas of high marsh environments or low-lying forest are ideal for detecting small changes in elevation where assemblage changes are rapid and clear. Subsidence in these areas would involve a substantial increase in salinity and therefore a substantial change in species assemblages. And an uplift event would be reflected by an increase in the number and species of thecamoebians.

Jennings and Nelson (1992) came to the conclusion, after examining a number of east and west coast marshes in North America, that vertical ranges of high and low marsh zones, especially on the west coast, limit the precision of estimated submergence. To alleviate these types of problems a detailed transect examination would be required to identify widely recognized subzones within each of high, mid and low marsh.

In many areas the knowledge of accurate and precise earthquake dating can result in the development of cyclic-seismicity, where for example a certain magnitude earthquake can be expected at an interval of 200-400 years. However these kinds of time frames cannot be used for planning purposes.

The timing of these precursor events is important because they provide a closely defined time frame in which earthquakes could be forecast. If we know that precursor events tend to begin between 2-4 years prior to the earthquake, then an early warning system could be established. Since over half of the world's population inhabits coastal areas, of which many are tectonically active, the importance of being able to forecast (within a few years) an earthquake event could have a resounding effect on those populations.

Because the study site lies along the Cascadian Subduction zone, which runs north-south from Alaska to northern California, any mega-thrust faulting would affect the entire length of the suture with the same mechanism, but not necessarily at the same time. This may be evident in the case of the Alaska 1964 earthquake which may reflect transition 2 in this Netarts Bay, Oregon study. The 1998 study by Shennan et al (1998b) indicated that there was a hint of a precursor but those were prehistoric events. The Alaska 1964 earthquake, where the exact timing, to within a few minutes is known, provides the confidence to interpret the Oregon events and any others that might be detected in the future (in California, Washington, and British Columbia). Although these areas are several thousand kilometres away from each other, they represent the same type of tectonic zone and react similarly in individual events. Surficially the two areas are separated tectonically by a hundred or so perpendicular strike-slip faults that break up the Cascadian Subduction zone, but it is deep-rooted mega-thrust earthquakes that cause seismic related movement along its entire length.

Chapter Six: Conclusions

6.1 Final conclusions

From the four transitions examined for precursor events to mega-thrust earthquakes, in this study, transition 1 reflected an uplift event which could be interpreted as non-seismic sediment infilling; transitions 2-4 represent submergence events. Transition 2 and 3 show strong precursor evidence, while transition 4 evidence is weaker perhaps due to erosion of peat during instantaneous tsunami deposition. Transitions 2-4 also follow the four-phase theory developed by Shennan et al. (1999) from the observed historic 1964 Alaska mega-thrust earthquake.

All four transitions show a decrease in total number of species and total number of individuals (per 10cc) throughout the minerogenic layers inferred as "tsunami" deposits. Evidence prior to the deposit displays a change in microfaunal assemblage and zonation which is not concurrent with storm or barrier breach occurrences. Also noted is the fine grain size of the minerogenic layer and lack of microfossils present within them.

6.2 Recommendations for future work

Radiocarbon dating of each transition zone would alleviate the assumptions between those dates done by Darienzo and Peterson, (1990); and Darienzo et al., (1994) and their correlation to this study because they were inferred from mean tide level, this would provide more accurate dates.

A transect of cores at the same site would provide more accurate subzone identifications with each of high, mid and low marsh. These subzones play a vital role in determining land (relative to sea-level) uplift/submergence and the amount of that movement.

Further studies into precursor events for mega-thrust earthquakes would require a number of large projects detailing microfossil marsh zonation to detect subzones necessary for submergenge/emergence relative land movement. These projects would involve precise stratigraphic and biostratigraphic correlation along transects of cores at specific sites to determine zonation for each area concerned.

Future work into known mega-thrust earthquake events (around the world) could provide necessary evidence to determine a largely applicable earthquake precursor event theory similar to the "earthquake deformation cycle" developed in Europe.

Taxonomy

Taxonomy

Benthic foraminifera

Arenoparrella mexicana (Kornfeld)

Trochammina inflata (Montagu) var. *mexicana* Kornfeld, 1931, p. 86, pl. 13, **Fig.**5.

Arenoparella mexicana (Kornfeld). Andersen, 1951, p. 31, **Fig.** 1; Phleger, 1954, p.636, pl. 1, figs. 12-14; Scott and Medioli 1908b, p. 35, pl. 4, figs. 8-11; Scott et al., 1990, p. 729, figs. pl. 1, figs. pl. 1, figs 7a-c; Scott et al., 1991, p. 384, pl. 1, figs. 16, 17.

Remarks: Test agglutinated, trochospiral with supplementary apertures on the apertural face which differentiate the genus from other trochospiral forms. This species is typical of high marsh environments.

(Scott et al., 2001)

Haplophragmoides wilberti (Anderson)

Fig. 1.6

Haplophragmoides wilberti Anderson, 1953, p. 21, pl. 4, fig. 7; Boltovskoy and Vidarte, 1977, p. 39, pl. 3, fig. 3; Zaninettie et al., 1977, pl. 1, figs. 12,13.

Remarks: Often difficult to differentiate between *H. wilberti* and *H. manilaensis*, the two are sometimes synonymous in certain environments. This species is typical of high marsh and brackish environments, but dominates in warmer climates. (Scott et al., 1991)

Miliammina fusca

Fig.1.6

Quinqueloculina fusca Brady, 1870, p. 286, pl. 11, figs. 2, 3.

Miliammina fusca (Brady) Phleger and Walton, 1950, p.280, pl. 1, figs. 19a, b; Phleger, 1954, p. 642, pl. 2, figs. 22, 23; Scott et al., 1977, p. 1579, pl. 2, figs. 8,9; Schafer and Cole, 1978, p. 28, pl. 12, **Fig.** 2; Scott and Medioli, 1980b, p. 40, pl. 2, figs. 1-3. Scott et al., 1991, p. 386, pl. 1, **Fig.** 14.

Remarks: Test agglutinated, coiled in a "quinqueloculine" pattern. This species occurs almost worldwide in low salinity low marsh and upper estuarine areas. (Scott et al., 2001)

Tiphotrocha comprimata (Cushman and Bronnmann)

Trochammina comprimata Cushman and Bronnimann, 1948, p. 41, pl. 8, figs. 1-3; Phleger, 1954, p.646, pl. 3, figs. 20, 21.

Tiphotrocha comprimata (Cushman and Bronnimann). Saunders, 1957, p. 11, pl. 4, figs. 1-4; Scott et al., 1977, p. 1579, pl. 4, figs. 3,4; Scott and Medioli, 1980b, p. 44, pl. 5, figs. 1-3; Scott et al., 1990, pl. 1, figs. 10a,b; Scott et al., 1991, p.388, pl. 2, figs. 5,6.

Remarks: Test agglutinated, trochospiral, ventral side somewhat concave. It is distinguished form *Trochammina* by a siphon-like extension to the aperture in the umbilical area. This species is common in middle and high marsh environments and in brackish areas, except for the Pacific basin. (Scott et al., 2001)

Trochammina inflata (Montagu)

Nautilus inflatus Montagu, 1803, p. 522, pl. 14, **Fig.** 3.

Rotalina inflata Williamson, 1858, p. 50, pl. 4, figs. 93,94.

Trochammina inflata (Montagu). Parker and Jones, 1859, p. 347. Phleger, 1954, p. 646, pl. 3., figs. 22,23; Scott et al., 1977, p. 1579, pl. 4, figs. 6,7; Scott and Medioli, 1980b, p.44, pl. 3, figs. 12-14; pl. 4, figs. 1-3, Scott et al., 1990, p. 733, pl. 1, figs. 3a,b; Scott et al., 1991, p. 388, pl. 2, figs. 7,8; Scott et al., 1995, p. 294, figs. 6.10-17.

Remarks: Test agglutinated, trochospiral, chambers rather inflated, increasing in size gradually; aperture a low arch with a bordering lip. This is the type of the genus *Trochammina*. This is perhaps the best known and most distinctive of all the endemic marsh species as well as being one of the earliest species ever described. It characterizes high marsh environments worldwide. (Scott et al., 2001)

Trochammina macrescens Brady

Fig. 1.6

Trochammina inflata (Montagu) var. *macrescens* Brady, 1870, p. 290, pl. 11, **Fig.** 5. Scott, 1976, p. 320, pl. 1, figs. 4-7; Scott et al, 1977, pl. 4, figs. 6,7.

Jadammina polystoma Bartenskein and Brand, 1938, p. 381, figs. 1,2.

Trochammina macrescens Brady. Parker, 1952, p. 460, pl. 3, **Fig.** 3. Phleger, 1954, p. 646, p.l. 3, **Fig.** 24; Scott and Medioli, 1908b, p. 44, pl. 3, figs. 1-12; Scott et al., 1990, p. 733, pl. 1, figs. 1a,b,2a-c; Scott et al., 1991, p. 388, pl. 2, figs. 10, 11; Scott et al., 1995, p. 294, figs. 6.6-8.

Remarks: This species was first listed as a variety of *T. inflata* – from which it differs in being more compressed – but its distribution tends to be limited to somewhat lower salinity conditions. A high salinity ecophenotype, *T. polystoma,* often occurs with *T. inflata.* This high salinity form is sometimes called *Jadammina polystoma. T. macrescens* forms, when they occur by themselves in high numbers, generally indicate a very narrow zone near higher high water. (Scott et al., 2001)

Trochammina ochracea (Williamson)

Rotalina ochracea Williamson, 1858, p. 55, pl. 4, **Fig.** 113.

Trochammina squamata Parker and Jones, 1865, p. 407, pl. 15, figs. 30,31. Scott and Medioli, 1980b, p. 45, pl. 4, figs. 6,7;

Trochammina ochracea (Williamson). Cushman, 1920, p. 75, pl. 15, **Fig.** 3; Scott and Medioli, 1980b, p. 45, pl. 4, figs. 4,5.

Remarks: *T. ochracea* is distinguished from the previous two species of Trochammina by being very falt and concave ventrally. The distribution of this species is very hard to define because it shows up in some very strange places, such as high marsh areas in Tierra del Fuago and Alaska, as well as in upper estuarine areas in Nova Scotia and most oddly in reefs of Bermuda (Javaux, 1999). This species is believed to be opportunistic. (Scott et al., 2001)

Thecamoebians

Centropyxis aculeata (Ehrenberg), 1832 ab (Ehreberg) **1830**

Fig. 1.7

Arcella aculeate Ehrenberg, 1832 (ab Ehrenberg, 1830, p. 60, nomen nudum), p. 91.

Centropyxis excentricus (Cushman and Bronnimann). Scott, 1976, p. 320, pl. 1, figs. 1,2; Scott et al., 1977, p. 1578, pl. 1, figs. 1,2; Scott et al., 1980, p. 224, pl. 1, figs. 1-3.

Centropyxis aculeate (Ehrenberg). Stein, 1859, p. 43. Medioli and Scott, 1983, p. 39, pl. 7, figs. 10-19; Scott and Medioli, 1983, p. 819, **Fig.** 9I; Patterson et al., 1985, p. 134, pl. 4, figs. 1-7; Scott et al., 1991. p. 384, pl. 1, figs 7-9.

Description – Test depressed; although quite variable it can be described as beret-shaped; in dorsal view, usually large and more or less circular, anterior sloping at 15 to 40 degrees; posterior slope more pronounced; height: length ratio usually low (mostly 0,4 to 0.5). Aperture subcentral, usually slightly anterior, invaginated. Spines not always present; when present, mostly concentrated along the posterior margin. Test basically organic, mature specimens usually covered with somewhat loose, amorphous, siliceous, particles, in most cases completely covering the membrane.

Approximate diameter: 100-300um.

Habitat: Fresh or slightly brackish water. (Scott et al., 2001)

Centropyxis constricta (Ehrenberg) 1843

Fig. 1.7

Arcella constricta Ehrenberg, 1843, p. 410, pl. 4, **Fig.** 35, pl. 5, **Fig.** 1.

Difflugia constricta (Ehrenberg). Leidy, 1879, p. 120, pl. 18, figs. 8-55.

Urnulina compressa Cushman, 1930, p. 15, pl. 1, **Fig.** 2. Parker, 1952, p. 460, pl.1, **Fig.** 9; Scott et al., 1977, p. 1578, pl. figs. 7,8; Scott et al., 1980, p. 224, pl. 1, figs. 13-15.

Centropyxis constricta (Ehrenberg). Deflandre, 1929, p. 340, text-figs. 6-67. Medioli and Scott, 1983, p. 41, pl. 7, figs. 1-9; Scott and Medioli, 1983, p.819, **Fig.** 9K; Patterson et al., 1985, p. 134, pl. 4, figs. 8-14; Scott et al., 1991, p. 384, pl. 1, **Fig.** 4.

Description: Test much less depressed than in *C. aculeate* and usually elliptical in dorsal view, with a profile usually raised posteriorly. Anterior angle 40 to 65 degrees. Fundus raised in uppermost position. Ventral side often relatively small, with invaginated aperture in anteromarginal position. Height/length ratio is typically high (usually 0.5 to 1.1). The fundus often carries two or more spires, as is common in most forms of Centropyxis. Test largely organic, often completely covered with mineral particles of various nature.

Approximate length: 100-400 um.

Habitat: Fresh water or slightly brackish. (Scott et al., 2001)

Cucurbitella tricuspis (Carter) 1856

Difflugia tricuspis Carter, 1856, p. 221, pl. 7, **Fig.** 80. Medioli and Scott, 1983, p. 28, pl. 4, figs. 5-19; Scott and Medioli, 1983, p. 818, **Fig.** 9Q,R; Patterson et al., 1985, p.134, pl. 2, figs. 15,16; Haman, 1986, p. 47, pl. 1, figs. 1-14; pl. 2, figs. 1-12.

Cucurbitella tricuspis (Carter). Medioli et al., 1987, p. 42, pl. 1, figs. 1-10; pl. 2, figs. 1-10; pl. 3, figs. 1-7; pl. 4, figs. 1-9.

Description: Test subspherical to ovate, either autogenous with "cauliflower" or "root-like" microstructures, or largely xenogenous with organic or mineral xenosomes (depending on availability). Aperture form irregularly subcircular to regular lobate with regular denticles, often surrounded by more or less complicated organic collar. The collar can become expanded and complicated to the point of forming a sort of second chamber with the aperture itself becoming invaginated to form a typical "*Cucurbitella*-structure".

Approximate diameter: 30- 160 um.

Habitat: Fresh water. During the summer, it can live as a "pseudoplanktic" form in an apparently parasitic relationship with the filamentous alga *Spyrogyra* which forms floating mats in eutrophic lakes. Autogenous forms are usually produced during this period. During the other seasons, it falls to the bottom and lives as a normal benthic form. Xenogenous tests are usually produced during the benthic stage. For a detailed description of the life cycle of this genus, see: Medioli et al. (1987). The xenogenous forms differ form *D. corona* because the latter normally has more than six indentations in the aperture. Not infrequently, however, forms can be found with intermediate numbers of lobes, in these cases identification becomes problematic. *C. tricuspis,* however is usually considerably smaller than *D. corona.* (Scott et al., 2001)

Heleopera sphagni (Leidy) 1874

Difflugis (Nebela) *sphagni* Leidy, 1874, p. 15.

Heleopera sphagni (Leidy). Cash and Hopkinson, 1909, p. 143, pl. 30, figs. 4-9. Medioli and Scott, 1983, p. 37, pl. 6, figs. 15-18; Scott and Medioli, 1983, p. 819, **Fig.** 9E.

Description: Test strongly compressed, ovoid; oral pole narrower in broadside view. In those tests that are mode of foreign idiosomes and are apparently autogenous, the mouth forms an elongated, narrow ellipse with acute commissures. The tests are made of mineral xenosomes usually have a wider, oval aperture that becomes almost subcircular in extreme cases. Commonly, coarse xenosomes tend to concentrate at the fundus. In fossil material, strongly mineral forms appear to be selectively preserved while forms with abundant autogenous plates are almost completely absent.

Approximate maximum width: 50-120 um.

Habitat: Fresh water, common in *Sphagnum* bogs. (Scott et al., 2001)

Appendix A

Transition 1
Transition 2
Transition 3
Transition 4

Each of the four tables displays the total number of species and total number of individuals per 10 cc as real numbers. All other data is a percentage of the total number of individuals per 10 cc. Each of the species found is listed with the percentage found at each centimetre interval.

Transition 1

Depth in core (cm)	102	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	125	130
Total # of species	7	7	6	6	5	6	7	3	4	6	10	7	6	5	4	7	8	7	4	5
Total # of individuals per10cc	2744	2280	4768	4256	4640	1848	536	280	760	1720	5512	5000	4872	4624	9232	4640	5064	5216	2544	1620
Arenoparella mexicana	5.8	11.2	11.4	4.5	5.9	1.3	6	0	0	0	1.6	0	0.3	0	0	4.5	1.6	4	0	0
Centropyxis aculeata*	0	0	0	0	0	0	0	0	0	0	2.8	1.3	0	0	0	0	0	0	0	10.9
Centropyxis constricta*	0	0	0	0	0	0	0	0	0	0	4.4	1.9	0	0	0	0	0	0	0	5.9
Cucurbitella tricuspis*	0	0	0	0	0	0	0	0	0	0	0.4	0	0	0	0	0	0	0	0	0
Haplophragmoides wilberti	3.2	2.8	5.7	4.5	5.2	3	1.5	0	0	0	0.4	4.5	0.5	0	0	2.6	7.9	11	0	14.8
Heleopera sphagni*	0	0	0	0	0	0	0	0	0	0	1.2	0.5	0	0	0	0	0	0	0	0
Miliammina fusca	2.6	1.4	5	2.3	0	0	3	0	0	0	7.8	0	1	1.2	1.4	2.1	4.4	3.7	8.2	0
Tiphotrocha comprimata	3.8	6	7.7	7.1	8.3	1.7	3	0	4.2	2.33	5.1	3.2	3.6	3.5	0	2.4	1.9	9.5	0	0
Trochammina inflata	30.9	26.6	31.2	28.6	12.1	7.4	16.4	3.8	6.31	6.5	7.7	4.4	3.9	30.3	52.6	45.5	32.2	21.2	44	15.8
Trochammina macrescens f. macrescens	52.2	51.2	38.8	53	68.6	85.6	58.2	92.3	88.4	84	68.7	84	91	38.8	33.8	35.5	43	43.6	45.3	50.4
Trochammina macrescens f. polystoma	0	0	0	0	0	0	0	0	0	0	0	0	0	26.3	12.2	7.2	3.8	0	0	0
Trochammina orchracea	0.9	0.7	0	0	0	3	11.94	3.84	1	2.33	0	0	0	0	0	0	5.2	7.1	2.5	0

Transition2

Depth in core (cm)	131	132	133	134	135	136	137	138	139	140	141
Total # of species	5	4	2	2	2	2	2	2	2	2	5
Total # of ind. per 10cc	1620	464	416	226	400	488	232	624	176	304	1512
Arenoparella mexicana	0	0	0	0	0	0	0	0	0	0	0
Centropyxis aculeata*	10.9	6.9	0	0	0	0	0	0	0	0	0
Centropyxis constricta*	5.9	6.9	0	0	0	0	0	0	0	0	0
Haplophragmoides wilbeti	14.8	0	0	0	0	0	0	0	0	0	1.6
Miliammina fusca	0	0	0	0	0	0	0	0	0	0	0
Tiphotrocha comprimata	0	0	0	0	0	0	0	0	0	0	3.2
Trochammina inflata	15.8	17.2	11.5	21	44	30	6.9	31	45	37	35
Trochammina macrescens f. macrescens	50.4	69	88.5	79	56	70.5	93.1	69	55	63.2	58.2
Trochammina macrescens f. polystoma	0	0	0	0	0	0	0	0	0	0	0
Trochammina orchracea	0	0	0	0	0	0	0	0	0	0	2.1

Depth in core (cm)	142	143	144	145	146	147	148	155	161
Total # of species	5	5	5	6	5	6	4	4	3
Total # of ind. per 10cc	2216	4348	4592	4336	7936	3280	4064	2512	1184
Arenoparella mexicana	0	0	0	7	2.2	3.9	0	0	0
Centropyxis aculeata*	0	0	0	0	0	0	0	0	0
Centropyxis constricta*	0	0	0	0	0	0	0	0	0
Haplophragmoides wilbeti	5.4	24.3	24.4	14.4	7.3	5.4	2	7	1.4
Miliammina fusca	0	0	0	0	0	0	0	0	0
Tiphotrocha comprimata	3.6	2	2.8	1.8	1.2	0.5	0	0	0
Trochammina inflata	26	9.6	8.4	14.4	8.9	7.8	6.7	8.3	21.6
Trochammina macrescens f. macrescens	63.5	63	63.8	60	80	80	89.8	82	77
Trochammina macrescens f. polystoma	0	0	0	3.3	0	0	0	0	0
Trochammina orchracea	1.4	1.1	0.7	2.6	0	2.4	1.6	2.5	0

Transition3

Depth in core (cm)	167	173	177	180	181	182	183	184	185	186	187	188	189	190	191	192
Total # of species	4	4	4	1	0	1	0	1	0	1	2	5	4	5	4	2
Total # of ind. per 10cc	2816	1168	800	8	0	8	0	8	0	24	128	2714	2384	1920	2064	1120
Arenoparella mexicana	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides wilberti	3.4	6.8	12	0	0	0	0	0	0	0	0	2.9	2.7	9.2	2.3	12.8
Miliammina fusca	0	0	28	0	0	0	0	0	0	0	0	0	0	2.5	1.5	0
Tiphotrocha comprimata	2.3	2.7	0	0	0	0	0	0	0	0	0	1.8	0	0	0	0
Trochammina inflata	10.2	9.6	10	0	0	0	0	0	0	0	12.5	11.8	6.7	2.5	4.7	0
Trochammina macrescens f. macrescens	84	80.8	50	8	0	8	0	8	0	24	88	78	89	81.6	91.5	87.1
Trochammina macrescens f. polystoma	0	0	0	0	0	0	0	0	0	0	0	5.1	2	0	0	0
Trochammina orchracea	0	0	0	0	0	0	0	0	0	0	0	0	0	4.2	0	0

Depth in core (cm)	193	194	195	196	197	198	199	200	203
Total # of species	3	3	4	4	3	2	3	2	3
Total # of ind. per 10cc	1392	2152	1990	2738	2752	2896	2992	2618	2736
Arenoparella mexicana	0	0	0	0	0	0	3.7	0	0
Haplophragmoides wilberti	13.8	8.9	10.5	1.8	3.6	0	0.53	1.2	7
Miliammina fusca	0	0	0	0	0	0	0	0	2.9
Tiphotrocha comprimata	0	0	0	0	0	0	0	0	0
Trochammina inflata	10.3	5.2	1.6	3.6	4.1	4.9	0	0	0
Trochammina macrescens f. macrescens	76	85.9	86.3	93.5	92.4	95	95.7	98.7	90
Trochammina macrescens f. polystoma	0	0	0	0	0	0	0	0	0
Trochammina orchracea	0	0	1.6	1.2	0	0	0	0	0

Depth in core (cm)	260	261	262	263	264	265	266	267	268	269	270	271	272
Total # of species	2	3	2	2	1	1	2	1	1	2	2	1	3
Total # of ind. per 10cc	304	384	384	800	178	128	80	48	96	66	128	48	608
Arenoparella mexicana	0	0	0	0	0	0	0	0	0	0	0	0	2.7
Haplophragmoides wilberti	0	12.5	4.2	6	0	0	0	0	0	0	0	0	0
Miliammina fusca	0	0	0	0	0	0	20	0	0	24.2	0	0	5.2
Tiphotrocha comprimata	0	0	0	0	0	0	0	0	0	0	0	0	0
Trochammina inflata	21	4.2	0	0	0	0	0	0	0	0	12.5	0	0
Trochammina macrescens f. macrescens	79	79.1	95.8	94	100	100	80	100	100	72.7	87.5	100	92.1
Trochammina macrescens f. polystoma	0	0	0	0	0	0	0	0	0	0	0	0	0

Depth in core (cm)	273	274	275	276	277	278	279	280	281	282	283	284	285
Total # of species	5	4	4	3	2	3	2	2	2	2	2	2	2
Total # of ind. per 10cc	3360	1632	3408	1264	2296	3648	2784	3712	6144	2338	3152	4184	4328
Arenoparella mexicana	1.4	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides wilberti	13.3	5.9	4.7	6.9	6.9	6.1	6.3	2.2	5.5	12	7.9	12.2	9.7
Miliammina fusca	3.3	5.9	2.3	3.8	0	0	0	0	0	0	0	0	0
Tiphotrocha comprimata	0	0	0	0	0	1.1	0	0	0	0	0	0	0
Trochammina inflata	0.9	6.9	5.6	0	0	0	0	0	0	0	0	0	0
Trochammina macrescens f. macrescens	81	81.4	87.3	91.1	93	92.7	93.6	97.8	94.5	88	92.1	87.8	90.2
Trochammina macrescens f. polystoma	0	0	0	0	0	0	0	0	0	0	0	0	0

Depth in core (cm)	286	287	288	289	290
Total # of species	2	2	2	2	2
Total # of ind. per 10cc	4112	3752	3168	2384	2770
Arenoparella mexicana	0	0	0	0	0
Haplophragmoides wilberti	3.1	11.9	11.6	12.4	15.6
Miliammina fusca	0	0	0	0	0
Tiphotrocha comprimata	0	0	0	0	0
Trochammina inflata	0	0	0	0	0
Trochammina macrescens f. macrescens	96.9	88	88.4	87.6	84.4
Trochammina macrescens f. polystoma	0	0	0	0	0

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