UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Earthquake Hazards in the Pacific Northwest of the United States

Compiled by
A. M. Rogers
T.J. Walsh
W.J. Kockelman
G.R. Priest

DISCRIMINATION OF CLIMATIC, OCEANIC AND TECTONIC MECHANISMS OF CYCLIC MARSH BURIAL FROM ALSEA BAY, OREGON, U.S.A.

BY CURT D. PETERSON[1] AND MARK. E. DARIENZO[1]

Open-File Report 91-441-C

[1]Department of Geology, Portland State University, P.O. Box 751, Portland Oregon 97207

1991

Foreword

This paper is one of a series dealing with earthquake hazards of the Pacific Northwest, primarily in western Oregon and western Washington. This research represents the efforts of U.S. Geological Survey, university, and industry scientists in response to the Survey initiatives under the National Earthquake Hazards Reduction Program. Subject to Director's approval, these papers will appear collectively as U.S. Geological Survey Professional Paper 1560, tentatively titled "Assessing Earthquake Hazards and Reducing Risk in the Pacific Northwest." The U.S. Geological Survey Open-File series will serve as a preprint for the Professional Paper chapters that the editors and authors believe require early release. A single Open-File will also be published that includes only the abstracts of those papers not included in the pre-release. The papers to be included in the Professional Paper are:

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ABSTRACT

Late Holocene sequences of buried peaty horizons, 2 to 10 in number, from marsh cut banks and from 19 salt marsh core sites in Alsea Bay, Oregon have been analyzed for composition, lateral correlation and age. These analyses are used to discriminate between different mechanisms of marsh submergence and burial, including river flooding, ocean set-up, barrier spit breaching and coseismic subsidence. System wide marsh responses to abrupt, but persistent, submergence events in Alsea Bay are demonstrated by (1) lateral correlation of key peaty horizons over distances of up to 3 km, (2) consistent vertical trends in peaty burial units, generally including increasing organics and decreasing sand content upunit, and (3) close association of anomalous (sand-rich) tsunami deposits immediately overlying, buried peaty horizons. The study results rule out marsh burial by catastrophic climatic or oceanographic processes, and argue for episodic coastal submergence forced by abrupt coseismic subsidence in an active subduction zone.

An average recurrence interval of 500 yr is estimated from 8 repeat intervals of coseismic subsidence between 4,510 and 480 RCYBP. By comparison, an average recurrence interval of 340 yr is estimated from the three most recent repeat intervals of coseismic subsidence between 1,490 and 480 RCYBP. Recurrence intervals between successive burial events are found to range from 250 to 1,370 years (uncalibrated radiocarbon years). The average minimum magnitude of vertical subsidence in Alsea Bay (0.5-1 m) at 44.4° N latitude is substantially less than that reported for Netarts Bay (1-1.5 m) at 45.4°, but more than that for Siuslaw Bay (0-0.5 m) at 44.0°. This trend in average coseismic subsidence implies a coastline closure with a zero isobase south of 44° N, and a 90 km distance between the zero isobase and the trench off central Oregon. Finally, a high correspondence between marsh subsidence and tsunami (sand layer) deposition is observed in Alsea Bay, even though the estimated amount of local coastal subsidence (0.5-1 m) is small.

INTRODUCTION

Recent reports of episodic burial of marsh and wetland horizons by tidal flat muds from several tidal basins of Washington and Oregon have greatly increased the controversy over the neotectonics of the Cascadia continental margin (Atwater, 1987; Peterson et al., 1988). For example, evidence of alternating coastal uplift and subsidence might indicate active subduction of the oceanic Juan de Fuca plate under the continental North American plate (fig. 1). Such periodic coastal displacements are associated with coseismic subduction in the strongly coupled subduction zones of Chile, southeast Alaska, and Japan, among others (Plafker, 1972; Uyeda and Kanamori, 1979; Heaton and Hartzell, 1986).

Abrupt changes in relative tidal level are clearly required to produce the catastrophic burials of the supratidal vegetated surfaces by lower intertidal sediments, that are observed in some Cascadia tidal basins (Atwater, 1987 and 1988; Darienzo and Peterson, 1990). However, abrupt increases in the height of relative tidal level in some bays might be caused by mechanisms unrelated to either local or regional tectonics. Such non-tectonic mechanisms might include (1) river flooding, (2) ocean storm surges, (3) anomalous conditions of oceanic circulation, and (4) changes in tidal inlet morphology and in the associated basin tidal prism.

Up to half a dozen coastal submergence events have been documented in marsh and wetland deposits from large estuaries (Willapa Bay and Grays Harbor) in southern Washington (Atwater, 1987, 1988) and from smaller bays, including a barrier lagoon (Netarts Bay) in Oregon (Peterson and Darienzo, 1987; Darienzo and Peterson, 1990; fig. 1). Buried peats have also been found in two fluvially-dominated estuaries, Nehalem and Salmon Bays, to the north and south of Netarts Bay, respectively (Grant and McLaren, 1987; Grant, 1989). The buried peats in these different bays have been radiocarbon dated, and they range in age from about 350 to at least 3300 radiocarbon years before present (RCYBP) in Netarts Bay (Darienzo and Peterson, 1989), and from 300 to 5000 RCYBP in Willapa Bay (Atwater, 1988). In contrast, relatively long sections of continuous or nearly continuous peaty sediments, greater than 4 m in thickness, have been observed in Siuslaw Bay of the central Oregon coast (Nelson, 1987; fig.1).

Discrimination between tectonic and non-tectonic mechanisms of relative sea level change are critical to the correct interpretation of the submergence events documented in these bays and in other coastal sites of this active margin. Of particular concern in the Cascadia subduction zone margin is the possible misrepresentation of climatic or oceanographic rises in tidal level for regional events of abrupt coastal subsidence, i.e., an indication of interplate subduction earthquakes.

STUDY SITE SELECTION

In this investigation of coastal marsh stratigraphy from the central Oregon margin, we have selected a study site, Alsea Bay (fig. 1 and 2), that should provide evidence to clearly discriminate between climatic, oceanographic and tectonic mechanisms of marsh burial. For example, Alsea Bay includes marsh deposits that continuously extend across a wide range of estuarine environments. The different marsh sites should reflect either (A) effects from river flooding (limited to the upper estuarine reaches), (B) effects from ocean set-up, produced by offshore storms or anomalous oceanic circulation (limited to the middle and lower estuarine reaches), (C) effects from very recent and dramatic changes in tidal inlet morphology (limited to lower and middle estuarine reaches) or (D) effects of coseismic subsidence (system-wide events of persistent marsh submergence and burial).

The second reason for selecting this study site is that the hydrology and sedimentology of this small tidal basin have been previously studied in detail (Goodwin et al., 1970; Boley, 1973; McKenzie, 1975; Peterson et al., 1982; Peterson et al., 1984a,b). Of particular importance to the investigations of marsh burial mechanisms are the distinctive mineralogies of river and marine source sands in Alsea Bay (Peterson et al., 1982). The identification of sand sources in marsh sediments should firmly discriminate between seaward- and landward-directed sediment transport during the events of marsh burial. Finally, buried peaty horizons were known to exist widely in exposed tidal creek banks of the Alsea Bay marsh, their presence having been observed during previous reconnaissance surveys of the bay (Peterson, unpublished data).

In this report, we present the details of the Alsea Bay marsh stratigraphy, as established from coring the upper 2 to 7 m of the existing marsh in transects that extend across the lower and upper reaches of the estuary. Distinctive horizons in selected marsh cores have been analyzed for (1) relative abundance of organics, (2) sediment grain-size distribution, (3) sand source (marine or fluvial), and (4) radiocarbon age of buried peats. The results of this study demonstrate that the observed marsh stratigraphy in Alsea Bay clearly permits the discrimination of tectonic subsidence from potential non-tectonic mechanisms of marsh burial. Due to the wide range of marsh settings in Alsea Bay, we believe that the results from this study site should have relevance and application to other coastal marsh and wetland systems of the Cascadia margin.

POTENTIAL MECHANISMS OF MARSH BURIAL

Salt marshes grow within restricted ranges of tide level, i.e., upper intertidal to supratidal levels (fig. 3), as a function of plant tolerance to desiccation, salinity, and substrate stability (Niering and Warren, 1980). Emergence of the salt marsh above the reach of tides results in a transition to upland vegetation, while submergence to lower intertidal or subtidal levels results in burial of the salt marsh by tidal flat sediments. While meandering tidal channels can produce deposits that mimic 'emergent tidal flat to marsh sequences' (fig. 4), these deposits (1) do not overlie in situ (undisturbed) marsh surfaces, and (2) are only locally developed, i.e., within the back-filled meander bends of tidal channels. In contrast, the focus of this study is directed towards the investigation of broadly defined events of system-wide marsh emergence or submergence, that indicate relative changes in mean tidal level relative to the marsh system surface.

Gradual submergence and/or burial of salt marsh horizons are well known from late Holocene transgressive sequences on passive continental margins of the United States eastern and gulf coasts (Kraft, 1971; Redfield, 1972; Orson et al., 1985). The consistent trend of coastal submergence recorded in these passive margin marshes is due to eustatic sea level rise and/or local tectonic subsidence. In contrast, the cyclic alternations of marsh emergence and submergence observed in some Pacific Northwest bays must be produced by more dynamic, reversible processes of relative sea level change (Darienzo and Peterson, 1990). Several potential mechanisms that could be responsible for the episodic events of marsh burial recorded in coastal deposits of the Cascadia margin are outlined below.

RIVER FLOODING

Tidal basins of the Pacific Northwest coast vary greatly in their relative influence from tidal and river flow. In the fluvially dominated estuaries, the peak river discharge (during a tidal cycle) can exceed 50% of the basin tidal prism (Percy et al., 1974). The upper estuarine reaches, often constricted by steep-sided river valleys cut into the foot hills of the Coast Range, are the areas most susceptible to flooding by extreme discharge events. For example, extreme river flood events (100 year floods) in Alsea Bay, such as in 1890 and 1964 (>1,133 m^3s^{-1}) are known to have raised the river level by some 7 m above the average level (1.5 m at 47 m^3s^{-1}) at a river gauge station located at the head of tide, a distance of 26 km from the bay mouth (U.S.G.S. Water Resources Div. 1988). Fine and coarse grained sediments are transported down riverine-tidal channel axes of the upper estuarine reaches during winter months of maximum river discharge (Peterson et al., 1982; Peterson et al., 1984a,b). Conceivably, suspended river sediments could bury salt marsh surfaces in the constricted, upper estuarine reaches during extreme events of river discharge (fig. 5).

The resulting flood burial deposits (above the peaty marsh horizon) might include fining upward sequences, i.e., fine sand grading upward to silt and clay (fig. 6), that are typical of flood overbank deposition (Reineck and Singh, 1980 pp. 288-291). In addition, the coarsest sediments in basal layers above the buried marsh would be expected to diminish in relative abundance with increasing distance away from the riverine-tidal channel axis (fig. 6), and with increasing distance downstream of the constricted river valley. Finally, and most importantly, marsh burial deposits of sand should reflect the river source mineralogy if they are derived from flood overbank deposition.

OCEAN SET-UP

Onshore wind and water forcing prevail along the Pacific Northwest coast when offshore storms (cyclonic low pressure centers) approach land from the west or southwest (Smith, 1974). The resulting ocean set-up from local storm winds, and the associated low atmospheric pressure, increases tidal levels within the bays. For example, measured tidal levels of at least 1.2 meters above predicted tides in Yaquina Bay (located 15 km north of Alsea Bay) are known to result from extreme onshore winds (up to 90 knots) that force onshore mass transport (fig. 7; H. Pittock, unpublished data). While the effects of such storm set-up conditions on coastal marsh systems in the Pacific Northwest are not known, more extreme events (hurricanes) are known to have produced storm sediment layers (1-3 cm thick) in marsh systems of the United States Gulf coast (Rejmanek et al., 1988).

Longer periods of episodic sea-level rise can occur from anomalous conditions of climatic-oceanic circulation. Small increases in monthly mean sea level are produced from (1) seasonally persistent conditions of low atmospheric pressure (Huyer et al., 1979; Pittock et al., 1982), and (2) the northward coastal propagation of El Nino Southern Oscillation (ENSO) sea-level bulges (Enfield and Allen, 1980). In the latter case, equatorial eastward mass transport that results from the relaxation of equatorial trade winds, is diverted south and/or north at the continental margin. The sea level bulge then propagates along the margin as a coastally trapped Kelvin wave. Although the rises in the monthly mean sea levels along the Oregon and Washington coasts have historically been small, i.e., 10-30 centimeters (Enfield and Allen, 1980; Huyer et al., 1983), the long duration (months) of elevated sea level (fig. 8) could conceivably have an impact on tidal marshes, as discussed below.

Conditions of elevated sea levels from storm surges and/or anomalous oceanic circulation would increase the depth and fetch of intrabasin wind waves in the characteristically shallow bays of the Pacific Northwest (Peterson et al., 1984a). The tidal marshes of the broad, lower estuarine reaches that are exposed to direct ocean swells or intrabasin wind waves would be the most susceptible to burial by sediments resuspended and deposited during major storms. The burial horizons could conceivably contain layered sand and silt (Allen, 1984; vol 2, pp. 493-504), resulting from time-variable tidal currents and the storm resuspension of sediments from shallow sand and mud flats (fig. 9). Clay should not constitute a major fraction of the storm burial layers, as it is likely to be held in suspension during catastrophic storm events. In addition, the immediate sources of tidal flat sediments in the fluvially dominated estuaries, such as Alsea Bay, have a significant sand component (Peterson et al., 1984a). The coarse-grained components of the storm deposits should (1) reflect the sand source mineralogy of the nearby tidal flats from which they would be derived, and (2) diminish in relative abundance with increasing distance away from these sand flat sources.

CHANGES IN TIDAL LEVEL RANGE

All of the mechanisms of submergence discussed above involve temporary increases in mean tidal level. However, long-term changes in tidal level range might also impact marsh growth and deposition (Clark and Patterson, 1985; fig. 3). Such long-term changes in tidal level range can occur from variations in tidal inlet morphology which controls the tidal flow between the free ocean surface and the inshore tidal basin. Nearly all of the tidal basins on the open coasts of Washington, Oregon and northern California are fronted by sand spit barriers (Dingler and Clifton, 1991, in press). Tidal inlets to these bays are either cut through the barrier spit or are pinned against a resistant sea cliff by a barrier spit on one side, as is the case in Alsea Bay (fig. 2). The cross-sectional area of the sandy inlets are generally proportional to the size and corresponding tidal prism of the tidal basin (O'Brien, 1969). Nevertheless, variable wave climate and the resulting mobility of littoral sand can cause a net infilling or erosion of the tidal inlet, thereby reducing or increasing basin tidal flow, respectively.

A reduction in tidal flow (choking) across an inlet results in a diminished tidal prism within the tidal basin. For all but the most fluvially dominated estuaries, the decrease in tidal prism translates into a decreased, maximum tidal level in the broad, lower estuarine reaches. Conversely, opening of the inlet increases tidal range, thereby increasing the depth, but not the period, of salt marsh submergence during high tide. For example, a substantial 50% increase in tidal level range, above the equilibrium range of 2 m (MLLW-MHHW; Percy et al., 1974), could add an additional 0.5 m of submergence during high tides in Alsea Bay. This magnitude of additional periodic submergence is similar to mean tidal level changes that are produced by short term processes of ocean set-up as outlined above. The effects of changing tidal level range on existing marsh systems in the Pacific Northwest bays have not previously been examined. However, significant changes in tidal range could, arguably, stress marsh systems, resulting in diminished growth and/or possible burial by inorganic sediments.

SUBDUCTION ZONE TECTONICS

Finally, coastal tectonic movements might provide a non-climatic, -oceanic mechanism of episodic marsh burial in the convergent margin setting of the Pacific Northwest. Vertical coastal displacements (subsidence or uplift) can result from (1) the cyclic strain accumulation associated with frictional coupling between the overriding continental plate and subducting oceanic plate, and (2) strain release owing to rapid decoupling of the plate interface (Fitch and Scholtz, 1971; Savage, 1983). The direction of vertical displacement generally depends on the coastline position relative to a flexure line, i. e., zero isobase (Plafker and Kachadoorian, 1969), of the upper plate (fig. 10). However, local upper plate faults and folds can complicate this deformation pattern (Plafker, 1972). The tidal basins of the central Oregon coast could record coseismic subsidence events, if subduction is active and strongly coupled in this margin.

Marsh burial sequences produced by coseismic subsidence (tectonic and sediment settling components; Plafker and Kachadoorian; 1969) would (1) occur extensively as system-wide deposits and (2) probably consist of low-energy tidal flat deposits of finely laminated or bioturbated mud overlying the submerged marsh surface (fig. 11). Such laminated or bioturbated muds are most commonly deposited in the protected, tidal flat environments of the Pacific Northwest estuaries (Clifton and Phillips, 1980; Peterson et al., 1982). Of particular interest to neotectonic investigations of this coast is the potential for tsunami deposition associated with coseismic coastal displacement (Heaton and Hartzell, 1986). Evidence of tsunami deposits immediately above the buried marsh surface would strongly argue for marsh burial by coseismic subsidence (Atwater, 1987). Such tsunami deposits should reflect a marine source mineralogy and should diminish in thickness with increasing distance upriver, if they are indeed produced by landward-directed marine surges or bores.

FIELD AND LABORATORY PROCEDURES

Cut bank exposures of the Alsea Bay marsh from the north side of the South Channel and from both sides of the North Channel (fig. 2) were examined for evidence of distinct peaty horizons. Significantly, the cut banks (1-1.5 m vertical exposure) represent a continuous, circumferential exposure of the shallow stratigraphy developed in the Alsea Bay marsh system. Two buried peaty horizons and associated sandy layers were stratigraphically correlated on a meter-by-meter basis around the central marsh circumference and along the North Channel (fig. 12). A total of 62 stratigraphic sections (fig. 12) were measured along the central marsh circumference to the nearest centimeter for depth of two buried peaty horizons below the modern marsh surface.

A total of 21 cores (19 core sites) were taken to subsurface depths of 2-7 m along a four kilometer, west-east transect (sites 1-13) and in two shorter north-south transects (sites 21-18 and sites 19-17) as shown in figure 13. Of the 19 sites cored in Alsea Bay, a total of 15 sites are contained within or are immediately adjacent to the cut banks 'walked-out' for correlation of shallow peaty horizons, as discussed above (figs. 12 and 13). The west-east core transect extends from the middle estuarine reaches (exposed to storm-tidal processes) to the upper estuarine reaches (dominated by riverine-tidal processes) as defined by hydrography (McKenzie, 1975) and sediment dispersal patterns (Peterson et al., 1982). The two north-south core transects are oriented perpendicular to the south channel, the major conduit of riverine-tidal flow in the upper estuarine reaches (fig. 13). The Alsea River valley and fringing marshes narrow dramatically to the east (up river) of core site 12 (fig. 5). Core site 1 (at the western end of the transect) contains only two thin marsh horizons (25 cm thick) over barren tidal flat sand, and it probably represents the most westward position attained by the contiguous marsh system in late Holocene time (fig. 13).

Two types of marsh cores were taken in the study area: (1) continuous cores in ABS pipe (5 cm and 7.5 cm diameter), and (2) one meter long gouge cores (2.5 cm diameter) returned from successively deeper (1 m) intervals. The continuous cores were used for quantitative sediment analyses and for radiocarbon dating of peat horizons. The gouge cores, were used for (1) depth control at continuous core sites, (2) stratigraphic correlation between core sites, due to negligible sediment compaction during coring, and (3) additional quantitative sediment analyses.

The core sites were surveyed in to local mean tidal level (MTL) based on a tidal bench mark (Tidal bench mark, Oregon 943 4938) originally established from a temporary NOAA tide gauge station (adjacent to core site 12). Elevation surveys of most core sites and of the modern marsh and tidal flats (adjacent to core sites 20 and 17) were performed with an autolevel and rod (accuracy ±0.1 m MTL). The elevations of core sites 21, 6, 12 and 13 are estimated based on both marsh surface elevations from (1) adjacent core sites and (2) long distance sightings with the surveying level (accuracy ±0. 3 m MTL).

Marsh cores were returned to the lab for detailed examination, sediment subsampling and archival in the refrigerated core facility at Oregon State University. All core logs are referenced to 1 cm scales and visual descriptions of sediment texture and organic content are calibrated against analyzed core samples from core sites 21, 8 and 12. Selected sediment horizons at these three sites were analyzed for (1) sediment dry bulk density, after drying at 60°C for 24 hr (Gardner, 1965), (2) relative abundance of organic material, i.e, weight loss on ignition at 380°C for at least 10 hr (Andrejko et al., 1983), and (3) relative abundances of sand (sieve diameter > 0.062 mm) and silt/clay after organic oxidation by H_2O_2 (Folk, 1980).

Sand source mineralogy was established for selected core horizons from sites 2, 4, 9, 12, 15, 18, 19 and 21 by petrographic analysis of the heavy mineral fraction. At least 200 diagnostic mineral grains (pyroxenes) were counted per sample slide to estimate relative abundances of river and beach sand. River pyroxene minerals are angular, and are comprised solely of augite, while beach pyroxene minerals are rounded and contain an average hypersthene:augite ratio of 0.60 (Peterson et al., 1982; Peterson et al., 1984a,b). Measurements of grain roundness and of hypersthene:augite ratios are normalized to yield percent beach sand and percent river sand in the analyzed samples.

Approximate ages of marsh burial events are estimated by radiocarbon dating of the top 5-10 cm of selected buried peats from core site 9. The peats were hand picked, oven dried and sent to a commercial firm (Beta Analytic Inc.) for radiocarbon age determination. Standard pretreatment leaches were performed there to remove potential contaminants. Peat ages were adjusted by $^{12}C/^{13}C$ ratios and were calibrated from established tree ring calibration curves (Stuiver and Reimer, 1986). All peat ages are assumed to predate the corresponding burial events.

STUDY RESULTS

TIDAL ELEVATION RANGES OF THE MODERN MARSH

Modern marsh development in Alsea Bay is clearly zoned with respect to tidal levels as reported by Jefferson (1975). Our observations and measurements of marsh plant assemblages in Alsea Bay (table 1) indicate that the densely vegetated surfaces of the modern high marsh range between 1.4 and 1.8 m relative to mean tidal level (MTL). Spruce and alder trees (upland vegetation) are presently colonizing the highest marsh surfaces (>1.8 m MTL) on elevated channel banks and in landward marsh perimeters. The lowest tidal elevations of continuous marsh development (low marsh) range from 0.6 to 1.1 m, while isolated patches of colonizing marsh in protected settings occur between 0.3 and 0.6 m MTL. Unvegetated tidal flat sediments in the central and upper reaches of Alsea Bay typically reach elevations of 0.3-0.6 m MTL. In summary, the laterally continuous development of most of the modern salt marsh in Alsea Bay extends over a tidal range of one meter (0.6 to 1.6 m MTL). However, at least 90% of the modern marsh surface is restricted to a much narrower elevation range, i.e. the high marsh (1.4-1.8 m MTL).

The modern marsh surface thus serves as a well constrained tidal level datum. Depths and ages of prehistoric tidal marsh surfaces can be used similarly to record past changes in relative sea level position. However, specific indicators of high marsh, low marsh and colonizing marsh settings are needed to establish the elevations of the buried marsh surfaces relative to their corresponding paleo-tidal levels. One such indicator is the relative abundance of peaty material in the marsh subsurface. The organic content of the modern marsh substrate (rooted zone) decreases dramatically from the highest marsh elevations to the unvegetated tidal flats in Alsea Bay, as in other Oregon marsh systems (Darienzo and Peterson, 1990).

Generally speaking, as the marsh surface reaches supratidal elevations, the tidal-flood supply of inorganic clastics is shut off, and the percent of organic materials (peat) increase. Susequent oxidation can decrease the relative abundance of organics but can not increase it. Thus measures of percent organics in marsh sediments provide useful criteria for establishing minimum marsh elevations relative to corresponding sea levels. Diatoms and plant macrofossils can be equally valid criteria for paleotidal level in some marsh systems (Atwater, 1988; Darienzo and Peterson, 1990). However, the abrupt vertical transition from a fresh water diatom flora to an overlying brackish/marine flora, as seen in Netarts Bay cores (Darienzo and Peterson, 1990) is lacking in Alsea Bay cores. This is probably due to the strong influence of the Alsea River (fresh water) in the upper and middle estuarine reaches during winter months of high river discharge. Thus, diatoms were not used as paleotidal level indicators here. On the other hand, plant macrofossils, specifically *Triglochin maritimum* rhizomes (a frequent tidal flat colonizer), were identified in the cores, but only below about 1.5 m depth subsurface. The presence of *Triglochin* rhizomes at the base of several variably developed peats possibly indicates episodic environmental changes from a high marsh to a tidal flat setting.

Quantitative measurements of organic content from selected marsh horizons in Alsea Bay were performed to (1) establish relative abundances of organic material in modern marsh horizons with known tidal elelvations, (2) calibrate visual estimates of peat development with measured percent organics in marsh cores, and (3) document down core vartiation in percent organics in marsh cores. Measured organic matter in core samples from modern high marsh horizons (table 1) contained greater than 25% organics. By comparison, barren mud deposits in Oregon bays generally contain less than five percent organics (Powell, 1980; Darienzo and Peterson, 1990).

The transition between colonizing marsh and established low marsh elevations is often complicated by the patchy development of colonizing marsh plants. Therefore, an assignment of a representative organic content to this transition zone is somewhat arbitrary. Nevertheless, the examination of marsh cores from Alsea Bay indicates that a minimum value of 10% organics over a 5-10 cm depth interval can be used to discriminate between established low marsh horizons (table 1) and the colonizing marsh or algal mud flat horizons in Alsea Bay.

For puposes of cut bank and core log descriptions, the relative peat development in the Alsea Bay marshes is defined as follows: peat (>50% organics), muddy or sandy peat (25-50% organics), peaty mud/sand (15-25% organics), slightly peaty mud/sand (10-15% organics), rooted or slightly rooted mud/sand (5-10% organics) and barren mud or sand (<5% organics).

CUT BANK CORREALTIONS OF SHALLOW PEATY HORIZONS

As shown in figure 2, the central Alsea Bay marsh is cut by two major tidal channels, the South Channel and the North Channel. Due to modification of tidal flow in these channels at their upstream confluence, beginning in the early 1900's (Kauffman, pers. comm., 1985), the banks on both sides of the two channels have eroded. Marsh deposits are exposed to 1-1.5 m depth below the modern marsh surface along both sides of both channel banks. Cut banks are present, but are less well developed upstream of the confluence of the North and South Channels. The Alsea Bay marsh system is possibly unique within coastal Oregon and Washington in containing continuous cut bank exposures which extend both over 50% of its entire length (6 km east-west) and throughout some 50% of its interior perimeter length (13 km). A total of 6.4 km of cut bank exposures in the central marsh area were mapped for shallow marsh stratigraphy (fig. 12).

Cut bank exposures of the central Alsea Bay marsh revealed two prominent horizons of muddy peats at average depths of about one half meter and one meter below the modern marsh rooted zone. A weakly oxidized layer (1-2 cm thick) was also observed, although rarely, at about a quarter meter in depth below the modern marsh surface. A third peaty horizon was infrequently observed between depths of 1-1.5 m below the modern marsh, its exposure being limited by modern sedimentation along the channel banks. The two upper muddy peat horizons have gradational lower contacts with peaty muds or slightly peaty muds and have sharp upper contacts with thin (1-10 cm) sandy layers. The sandy layers above each of the upper buried peats are differentially eroded by tidal current and local wind wave scour to produce apparent slits, directly above each buried peat horizon, in the cut bank exposures (fig. 14).

The two upper buried peat horizons were nearly continuously correlated on a meter-by-meter basis over a distance of 4.5 km around the circumference of the central marsh island and along 1.9 km of the south bank of the North Channel (figs. 12 and 15). The depths to the tops of the two peat horizons are shown to vary from 32 to 95 cm (upper peat horizon) and from 62 to 128 cm (lower peat horizon) below the modern marsh surface (Appendix 1; fig. 15). Some of the apparent variability in the subsurface depths of the buried peat horizons was observed to result from local variation of the modern marsh elevations (roughly 1.1-1.8 m MTL; table 1), not shown in figure 15. However, the separation distance between the two buried peaty layers was also found to vary significantly, i.e., from 20 to 51 cm (Appendix 1).

MARSH VERTICAL SEQUENCES

The deeper stratigraphy of the Alsea Bay marsh is established on the basis detailed logs taken from west-east core transects (fig. 16A,B) and a north-south core transect (fig. 16C) of the central marsh system. Maximum core depths (subsurface) range from two meters (site 2) to seven meters (sites 8 and 9). Our hand coring devices were incapable of penetrating thick sandy horizons (0 to -1 m depth MTL) from either the lower bay marsh (sites 1, 2, 4 and 20) or the south channel banks (sites 17 and 18). By comparison, relatively deep cores (-4 to -5.5 m depth MTL) were consistently obtained from the central marsh (sites 7, 8, 9, 11 and 19) which is dominated by very fine grained deposits.

All of the analyzed cores from the Alsea Bay marsh demonstrate multiple horizons of peat or peaty mud (5-75 cm thick) which are often separated by very low organic (VLO) sediments (fig. 16A,B,C). The tops of the black peaty horizons (buried marsh surfaces) generally consist of sharp contacts (< 1 cm across) with overlying deposits. In contrast, the contact between the bottoms of the peaty horizons and the underlying VLO sediment are usually gradational, i.e., decreasing organic content downcore. An analysis of 95 individual peaty horizons (> 5 cm in thickness) from the 19 core sites establishes that 97 percent of the peat tops display sharp contacts, while 80 percent of the peat bottoms contain gradational contacts. These consistent changes in peat development define the tops and bottoms of distinct marsh horizons, even when intervening layers of VLO mud/sand are not present.

The layers of VLO sediments between the peaty horizons are quite variable in thickness and composition. The barren or slightly rooted mud layers are either finely laminated or homogeneous to the naked eye, and range from 2 cm to 125 cm in thickness (fig. 16A,B,C). The VLO layers generally decrease in thickness (> 50 cm to < 10 cm) upsection. Significantly, some of the youngest peaty horizons are separated by only very thin (1-2 cm) rooted mud or sand layers, such as that shown at about 1 m MTL in site 2. In contrast, thick basal layers (>50 cm thick) of barren sand or muddy sand occur below the peaty horizons in the western marsh sites (1, 2, 4, 18, and 20). These barren sediments probably represent exposed tidal flats in the western marsh sites.

Significantly, the bases of some VLO layers and of some peat horizons (0.5 to 1.5 m MTL) in the western marsh sites and in sites along the north channel of the central marsh are characteristically sand-rich (fig. 16A,B,C). The thin, structureless sands defined here as sediment capping layers (SCL), contrast with both the overlying laminated muds or peaty muds, and with the underlying peaty horizons. The observed SCLs in the Alsea Bay marsh cores range from 25 cm to less than 1 cm in thickness. The thicknesses of the SCLs generally decrease with distance from the northwestern bay marsh to the eastern confluence of the north channel, i.e., from site 21 to site 16 (figs. 13 and 16). Finally, the bases of the 2-3 uppermost peaty horizons are variably oxidized (orange brown color) in many of the marsh core sites (4, 7, 8, 10, 11, 13, 15, and 16), indicating temporary desiccation and exposure to oxidating conditions.

The vertical sequence of an SCL and/or VLO layer grading up into a fully developed peat represents a complete burial unit. However some burial units are preserved which locally do not contain an SCL or a VLO layer. The vertical repitition of burial units in Alsea Bay reflects a succession of marsh submergence events.

MARSH STRATIGRAPHIC CORRELATION

Using both the relative depths and numbers of peaty vertical sequences downcore, we have correlated key stratigraphic horizons between adjacent core sites. For example, three units of peat development in the uppermost 1.5 m of the central marsh are correlated between sites 8, 9, 10, 11, 16, and 19 (fig. 16C). Two out of these three units have been traced continuously over multikilometer distances in exposed cut banks of the south and north channels from the central marsh area (see Cut Bank Correlations Of Shallow Peaty Horizons above). A total of at least 11 units of peat development are observed to depths of -5.5 m MTL at sites 8 and 9, starting with the modern marsh (fig. 16C).

Similarly, distinct peaty horizons from the upper 1.5 m of the western and eastern marsh areas are stratigraphically correlated with key horizons of the the central marsh (fig. 16A,B,C). Vertical offsets of 10-30 cm between corresponding peat horizons from nearby core sites are relatively common in the western marsh area. These vertical offsets are consistent with the elevation differences (10-40 cm) of the modern marsh surface (table 1), and they probably reflect the variability of the older marsh elevations prior to burial (fig. 16A,B,C). By comparison, corresponding horizon elevations in the eastern marsh are relatively consistent, with the exception of the furthest upriver location (site 13). Site 13 is not included in the stratigraphic correlation of buried peat horizons due its anomalous stratigraphy.

It is not possible to confidently extend the deeper marsh stratigraphy (0 m to -5 m MTL) beyond the central marsh area. This is due both to (1) the shallow depths of core penetration in the sand rich western sites, and (2) the relatively poor preservation of peaty horizons or lack of marsh development below 0 m MTL in the western and eastern core transects. However, the broad correlation of the shallow peat horizons in the top two meters throughout most of the central, western and eastern marsh sites provides the necessary control to test several different mechanisms of marsh burial in Alsea Bay. The following sections will focus on these uppermost horizons.

QUANTITATIVE ANALYSES OF PEATY UNITS

Quantitative analyses of organic content and sediment grain size in the modern marsh and deeper burial units were performed for three core sites, i.e., site 21 (western marsh), site 8 (central marsh), and site 12 (eastern marsh). Analyses of the burial units, i.e., marsh tops (MT) and corresponding marsh bottoms (MB) or underlying VLO sediments (S), are used to (1) verify visual interpretations of core site stratigraphies, and (2) compare marsh response to burial processes in different estuarine settings. Finally, grain size analysis was performed on SCLs from site 21 to establish the variability of sand abundances between these anomalous sandy layers and the underlying peat tops.

As indicated in the marsh core logs (fig. 16B,C) the organic content and percentages of sand and mud in burial units from the central and eastern marsh vary systematically downcore (table 2). Organic contents, established by loss on ignition, increase by 1-3 fold from the bottoms to the tops of most burial units from sites 8 and 12 (fig. 17). In contrast, the percent abundances of sand in the inorganic fractions tend to decrease over the same intervals (fig. 18). Organic content and percent sand show the strongest inverse correlations in the lower stratigraphic sections (horizons 2, 3 and 4). These trends demonstrate a diminishing supply of inorganic sediments, particularly coarse size fractions, relative to organic material due to a decrease in tidal and river influence with the transition from colonizing or lower marsh to higher marsh settings.

By comparison, cyclic variations in either organic content or sand abundance are generally absent from the upper burial units in the western marsh site 21 (fig. 17 and 18). A significant increase in organic content above 2MB at this western site (21) corresponds to similar increases in the central (8) and eastern (12) sites. Whereas the lower burial units (3 and 4) in all three sites generally demonstrate upward transitions from colonizing marsh to low marsh (5-15% organics), the upper horizons (0 and 1) appear to include predominantly high marsh substrates (24-48% organics). The change in organic content from the 2MT to 2MB horizons at all three core sites bridge this lower tidal to higher tidal transition as shown by the vertical sequence of a colonizing or low marsh (5-10% organics) grading up to a high marsh (30-50% organics) (figs. 17 and 18). The dramatic change in organic content between the 2MT and 2MB horizons in these widely separated core sites further substantiates the stratigraphic correlations of buried peaty horizons in Alsea Bay.

Sediment grain size analyses of the SCLs from site 21 document substantial differences in the relative sand abundance between the thin SCLs and the underlying peat horizons (table 2). Extreme enrichment of the sand fraction was found at each of the sharp contacts between the SCLs and corresponding buried marsh surfaces in site 21 (fig. 19). For example, sand abundances increased from 0.9 percent at 6MT to 81.9 percent at 5SCL across this relatively deep contact, and from 8.9 percent at 2MT to 76.9 percent at 1SCL across this shallow contact. Relative sand abundances in marsh bottoms from site 21 are also substantially less than those measured in the SCLs (table 2; fig. 19), further demonstrating the unique composition and origin of the SCLs.

The relative sand abundances in SCLs from other sites generally decrease with (1) increasing distance up the north channel and (2) decreasing thickness of the SCLs themselves. It should be noted that the SCLs are identified by the relative enrichment of sand. However, some thin, fine grained deposits directly overlying buried peaty horizons in the central and eastern marsh areas (e.g., above 3MT sites 8 and 9) (fig. 16C) might correspond to the same event that deposited the sandy SCLs in the western marsh sites. In addition, no consistent sand enrichment is observed between the top peaty units (between OMB and 1MT) peaty units in the western or central marsh core sites.

MINERALOGY OF SEDIMENT CAPPING LAYERS

The heavy mineral assemblages of selected SCLs were investigated to establish the sources (river or marine) of these anomalous sand layers. The thickest SCLs (1SCL above 2MT, 2SCL above 3MT, and 4SCL above 5MT) are located along the northeast bay margin (sites 21, 20 and 15) and on up the north channel (site 19) as shown in figure 16A,C. Heavy mineral separates from these SCLs were analyzed for river and beach sand sources on the bases of both hypersthene:augite ratios and grain rounding (see Field and Laboratory Procedures above). Heavy mineral analysis of the sand fractions from underlying peat tops were also performed to establish any differences in sand sources between the anomalous SCLs and the buried peat horizons.

Sand source analyses were performed for representative cores of the north channel (sites 21, 15, 19) and of the south channel (sites 18, 4 and 12). The results of the analyses demonstrate striking variations in sand source composition between SCLs, and/or equivalent horizons in site 12, and the corresponding buried peat tops in the northern marsh sites (table 3). Although the river sand component dominates all of the analyzed sand fractions (53-100% river sand), the SCLs of the north bay and north channel sites are consistently enriched in the beach sand component. For example, the SCLs range from 14 percent to 47 percent beach sand at the western sites 21 and 15. In contrast, none of the underlying marsh top horizons exceed 10 percent beach sand (table 3).

Plots of SCL beach sand component for several sites extending up the north side of the bay (sites 21, 15, 19, and 12) show that for each SCL the percentage of the beach sand component decreases with increasing distance up the bay (fig. 20). By comparison, the two upper SCLs (1SCL and 2SCL) from the south channel (sites 18 and 4) yield little or no evidence of marine sand supply (<5% beach sand component). The beach sand percentages of 2SCL at sites 21, 15, 19 and 12 are plotted (fig. 21) on a map of modern sand composition contours in the bay, as previously reported in Peterson et al., 1982. The high abundances of the beach sand component (31-47%) at marsh sites 15 and 21 contrast sharply with adjacent tidal flat sands, averaging less than 10-20% of this marine-derived component (fig. 18). The nearest potential sand source (> 50% beach sand) for this SCL (up to 47% beach sand) is located some 1.5 km due west (seaward) of site 21. The decreasing beach sand percentages up the north channel also correspond to decreasing sand relative abundances and to decreasing sand layer thicknesses in the SCLs (fig. 16A,C).

The SCL trends established above collectively indicate the diminishing transport energy of landward-directed surges or bores with increasing distance away from the Alsea Bay mouth. The apparent attenuation of the surges occurs over a relatively short distance of only 5-7 km from the mouth, as established by the upchannel termination of sandy SCL deposition.

RADIOCARBON AGES OF PEATY HORIZONS

Selected peaty horizons (top 5-10 cm) in core site 9 and from one stratigraphic section (station 41) from the central marsh have been analyzed for radiocarbon age. A total of 8 peat radiocarbon ages and one radiocarbon age from a detrital wood fragment (2MT) in radiocarbon years before present (RCYBP) are shown in figure 22. As should be expected, the sample analyses show increasing age (480 RCYBP to 4,510 RCYBP) with increasing depth (1.1 m to -5.1 m MTL). The uppermost buried marsh (MT1) top yielded a radiocarbon value that could indicate an age that might be too young (160 RCYBP; fig. 22), because live roots from the modern marsh surface are known to descend through this peaty horizon. Recently decayed roots (not distinguished during processing) presumably added modern ^{14}C to this older layer.

To date the second buried marsh horizon (2MT) a detrital wood fragment (2 cm diameter conifer branch) from the top of the first buried peaty horizon at Stratigraphic Station 41 (fig. 12, Appendix 1) was utilized for radiocarbon analysis. The use of the detrital wood fragment circumvented the problem of modern root contamination in this shallow, buried marsh horizon. The ages of the wood fragment as well as the deeper peats are assumed to predate the timing of the corresponding events of marsh subsidence.

The deeper peat tops are estimated to have the following calibrated radiocarbon ages (cal yr BP) including: MT3 (561-903 yr BP), MT5 (1260-1530 cal yr BP), MT6 (1999-2349 cal yr BP), MT7 (2479-2783 cal yr BP), MT8 (2779-3205 cal yr BP) and MT9 (3168-3389 cal yr BP) (fig. 22). The fourth buried marsh top (MT4) was not radiocarbon dated due to potential contamination via descending roots from the overlying peat horizon. The deepest peat horizon cored (MT10 at -5.12 m MTL) represents the oldest buried marsh (4869-5319 cal yr BP) to be reported in the central Oregon margin. Its date extends the known period of episodic marsh burial in this region back to middle Holocene time. The total of at least 9 marsh subsidence events (fig. 22) that occurred over the period from 4,510 to 480 RCYBP yields an average recurrence interval of 500 years. This average recurrence interval is based on 8 subsidence intervals over the 4,000 year period.

DISCUSSION AND CONCLUSIONS

SYSTEM WIDE RESPONSE TO MARSH BURIAL EVENTS

Multiple horizons of buried peat or peaty mud, are found in cut banks of the central marsh system (figs. 12, 14 and 15) and in all of the Alsea Bay core sites analyzed (19 sites), including middle-upper estuarine, and natural channel levee environments (fig. 16A,B,C). The total number of peaty horizons (3-10) in each core site is generally proportional to the corresponding maximum depth of core penetration (-0.5 to -5.5 m depth MTL). While the successive development and preservation of peaty horizons must indicate an overall condition of relative sea level rise, the distinct burial units do reflect shorter term periods of relative sea level rise and fall. At least 80% of the individual peaty horizons analyzed contain both gradational lower contacts (gradual emergence) and sharp upper contacts (rapid submergence). Intervening layers of barren and/or rooted mud/sand are generally found between these individual peaty horizons.

These distinctive units of peat development define key stratigraphic horizons which are widely correlated throughout the central and eastern marsh, and western marsh (figs. 14, 15 and 16A,B,C). In addition, several anomalous SCLs in the western and central marsh sites (figs. 16A,C and 20) serve as particularly distinctive marker beds. Two out of the three uppermost peaty horizons, exposed in tidal creek banks of the central marsh, can be nearly continuously traced around a 4.5 km perimeter of the central marsh island and along an additional 1.9 km of the northwestern fringing marsh (figs. 12, 14 and 15). These are the peaty layers at approximate depths of 0.5 and 1 m depth below the modern marsh surface. These peaty layers correspond to core horizons 2MT and 3MT. In contrast, the weakly developed 1MT-0MB interval found in many of the core sites was only infrequently observed in cut banks. Futhermore, this occasionally oxidized horizon (1MT) generally lacked a well defined SCL or a significant decrease in organic content above the oxidized interval.

These direct observations of the lateral continuity of peaty horizons in cut banks substantiate the stratigraphic correlations of the 4-5 uppermost buried marsh surfaces identified in the upper two meters of marsh cores (fig. 16). In conclusion, several factors demonstrate a system-wide response to catastrophic events of marsh burial, including (1) continuous lateral correlation of two peaty horizons (2MT and 3MT) in cut banks of the central marsh system, (2) a similar number of downcore peaty horizons at equivalent depths between most adjacent core sites, and (3) the similarity of upper (sharp) and lower (gradiational) contacts of the peat horizons in nearly all of observed core sites.

The regular changes in the percent abundance of organics (increasing up sequence) and in percent abundance of sand (decreasing up sequence) in burial units from sites 8 and 12 indicate successive cycles of transition from a lower to higher marsh setting (fig. 17 and 18). The cycles of marsh burial and reestablishment, demonstrate that the burial events are associated with a persistent state of submergence of the marsh surfaces relative to mean tidal level. These late Holocene submergence events are similar to those reported for tidal basins of southwest Washington (Atwater, 1987; 1988) and of northwest Oregon (Peterson et al., 1988; Darienzo and Peterson, 1990).

RIVER FLOOD PROCESSES

River flooding is an important mechanism of sediment transport down the Alsea River channel in winter months of high river discharge (Peterson et al., 1982). However, predicted stratigraphic features of catastrophic, flood overbank deposition, including relatively thick sand sequences at the channel levee sites and near levee sites (fig. 6), were not observed in the upper estuarine marsh sites (fig. 16A,B,C). What is observed is a decrease in sand abundance upward within most of the burial units. As a marsh builds upward it extends beyond the reach of high velocity currents capable of carrying sand, thus lending credence to the assumed transition from lower to higher marsh settings at these sites (table 2; figs. 17 and 18). These results indicate periods of marsh vertical accretion by normal tidal-riverine processes of long term sedimentation rather than by events of catastrophic burial during extreme river floods. While fining up sequences are associated with the SCLs of the western and central marsh, these deposits could not have been supplied by river floods, since they contain anomalously high relative abundances of the marine sand component (fig. 20).

The lack of river flood evidence in the high tidal marshes of Alsea Bay is explained, in part, by reduced flood levels in the tidally-influenced estuarine reaches. Relative to the constricted river valleys of the estuarine tributaries, the tidally-influenced estuarine reaches are characterized by large increases in the areas of intertidal and lower supratidal surfaces (Percy et al., 1974). Consequently, high river stages have much reduced effects in these estuarine reaches where riverine-flood waters are spread out over the broad surfaces. In addition, high marsh flooding is limited to relatively brief intervals, i.e., during high tide cycles. Furthermore, Alsea Bay tidal levels, analyzed by McKenzie (1975) at a location just south of our core site 12 (fig. 13), demonstrate a decrease in measured tidal range relative to predicted tidal range during high river stages. The amplitude of the flood tidal waves in the upper estuarine reaches of Alsea Bay are dampened by at least 1 m during peak discharge events. The decrease in tidal amplitude further moderates the effect of high river discharge during flood tide periods.

Most important to the problem of high marsh burial by river flooding is the apparent confinement of coarse grained sediments to the riverine-tidal channels themselves. The sediments carried down the turbulent riverine channels of the uppermost estuarine reaches are likely to fall out of suspension during the period of decelerating river flow that leads up to flood tide slack water (maximum tidal elevation). As a result, the coarser river sediments, particularly sand, are unlikely to be deposited over the high marsh surfaces, which undergo the greatest submergence only during high tide. The river gravel, sand and coarsest silt work their way down the upper estuarine reaches via the subtidal and intertidal channel axes. Clay and fine silt, which either remain continuously in suspension or are intermittently resuspended, are effectively transported out of the estuary, to be dispersed in the marine environment (Peterson et al., 1984a,b).

In conclusion, the predicted effects of catastrophic river flooding (see Potential Mechanisms of Marsh Burial: River Flooding) as the mechanism of tidal marsh burial in Alsea Bay are violated by the following observations: (1) the lack of thick overbank flood deposits at the channel levees, (2) the upwards decrease in percent sand within burial units, indicating transitions from tidal flat/low marsh to high marsh tidal elevations, (3) the general thickening of SCLs, including marine sand components, with distance away from the constricted river valley, and (4) diminished effects of salt marsh submergence and burial by high river discharge due to hydrographic and sediment transport constraints in tidal basins.

OCEAN SET-UP PROCESSES

An alternative mechanism of marsh submergence and burial could possibly be produced by ocean set-up resulting from extreme ocean storm surges and/or anomalous oceanic circulation. While historic storm surges have been short-lived, e.g., rarely extending beyond a single tidal cycle, they invariably coincide with periods of maximum, wind wave generation over the shallow tidal flats, thereby greatly increasing the potential for sediment resuspension. The effects of intrabasin wind waves and/or storm surges have undoubtedly contributed sand and silt to the westernmost marsh sites of the middle estuarine reaches in Alsea Bay (sites 1, 2 and 21). For example, the four youngest marsh tops (OM-3MT)) in core site 21 generally exceed 10% sand (fig. 19 and table 2), while corresponding marsh tops from sites 8 and 12 average only 2.5% sand in 11 analyzed horizons. Mineralogical analysis of the sands from the upper four marsh tops in the western site 21 indicates a proximal source from the nearby tidal flats (figs. 20 and 21), confirming their origin by storm resuspension.

In contrast, the coarse sediment fractions in both the peaty horizons and the overlying sediments, excluding the SCLs, from the central and eastern marsh (sites 19 and 12) are almost exclusively composed of river supplied sand, but not sand from the broad tidal flats that are exposed to storm resuspension processes (tables 2 and 3). Ocean storm surges are clearly incapable of burying peats with resuspended tidal flat sands in the upper estuarine reaches of Alsea Bay. Finally, the sediments above buried marsh tops in the central marsh sites are predominantly comprised of silt and clay, and not the coarser size fractions (sand), that are assumed to be resuspended during major storms (fig. 9). Apparently, the brief periods of maximum onshore winds (hours rather than days) and the relatively low maximum velocities (generally under 100 knots) that characterize Pacific Northwest storms (fig. 7) are not sufficient to transport and deposit thick sediment sequences over broad marsh surfaces.

By comparison, longer periods (weeks-months) of elevated mean sea level might have a more significant impact on marsh development and/or burial, due to (1) the additive effects of submergence during spring tide extremes and (2) extended submergence during winter storms and high river discharge. The largest measured increase of monthly mean sea level (30 cm above a 10 year mean) occurred very recently (winter and spring of 1983) as a result of the 1982-83 ENSO event (fig. 8; Huyer et al., 1983). This was also a year of above average precipitation and high river discharge. However, close examinations of the modern marsh horizon (0MT) from the Alsea Bay core sites establish that no anomalous sedimentation or decrease in the relative abundance of organic material occurred from this most recent ENSO event of elevated sea level. The observed 30 cm rise in mean sea level did not result in marsh deterioration in Alsea Bay, and thus it provides a lower limit to the amount of submergence, i.e., greater than 30 cm, that is required to drown and bury a high marsh in this tidal basin, over a several month time scale. Longer lasting events (years) of ENSO related sea level rise are precluded by the relatively brief intervals of relaxed trade wind stress and corresponding Kelvin wave transport (Enfield and Allen, 1980).

In summary, the predicted effects of storm or oceanic current induced ocean set-up in producing marsh burial in Alsea Bay are precluded by (1) the observed restricted range of storm resuspension processes, i.e., storm resuspension deposition is limited to exposed, western marsh sites, (2) the moderate nature of northeast Pacific storms, which do not reach hurricane wind intensities or durations, and (3) the limited elevations and short durations (annual) of ENSO forced sea level bulges.

CHANGES IN TIDAL LEVEL RANGE

Marsh growth in Alsea Bay could potentially be impacted by changes in tidal level range due to changes in the bay spit-barrier morphology. Sandy tidal inlets do not completely close off in estuaries that are as large as Alsea Bay (O'Brien, 1969). However, adjustments in barrier-spit morphology can result in significant constriction or widening of the tidal inlets, producing corresponding changes in the tidal prism. For example, major changes in the cross-sectional area of the Alsea Bay tidal inlet recently occurred in association with an anomalous breaching and recovery of the Alsea Bay spit from 1985 to 1987 (Jackson and Rosenfeld, 1987; Peterson et al., 1990). The total cross-sectional area of the inlet increased from about 600 m^2 (prior to 1985) to at least 2,000 m^2 (December 1985), and then it finally returned to the pre-1985 condition by 1989 (fig. 23). This unusual event, initiated by beach sand displacement during the 1983 ENSO period (Komar, 1986), provides an excellent test of a changing tidal inlet geometry on mean tidal levels within the bay, and of the potential impacts of increased tidal level range on the bay marsh system.

The 400% increase in tidal inlet cross-sectional area in 1985, is estimated to have resulted in a greater than 60% increase in peak tidal flow through the Alsea Bay inlet (Jackson and Rosenfeld, 1987). The greater tidal flow increased the estimated bay surface:ocean surface level ratio from 0.71 (pre-1985) to 1.00 (1985). The nearly 30% increase in potential peak tidal levels in Alsea Bay could yield an additional 0.7 m of marsh submergence during maximum high tides (Jackson and Rosenfeld, 1987), a very substantial increase considering the equilibrium MHHW-MLLW tidal range of 2 m in Alsea Bay (table 1). However, close examinations of the modern marsh horizons from all of the study core sites revealed no observable effects of this major change in tidal level range on the gross development or the fine-scale stratigraphy of the modern marsh top (0MT). These results demonstrate that similar pre-historic changes in the Alsea Bay tidal inlet could not have produced the effects of marsh submergence and burial that are recorded throughout the bay marsh system.

COSEISMIC SUBSIDENCE

Perhaps the strongest evidence against the burial of the Alsea Bay marsh by relatively brief periods of ocean set-up, anomalous oceanic circulation or changing tidal level range is the observed asymmetry of peat development. Greater than 80 percent of the peaty horizons from the Alsea Bay core sites display both sharp upper contacts (marsh tops) and gradational lower contacts (lower marsh or colonizing marsh substrates). These vertical trends in peat development indicate conditions of abrupt marsh submergence (upper contacts) followed by gradual marsh emergence (lower contacts). The strong asymmetry of peat development is remarkably consistent throughout the entire marsh system (fig. 16A,B,C) demonstrating a system-wide response to episodic marsh submergence and/or burial, followed by marsh emergence.

Finally, the marsh burial sequences, which include relatively thick layers of finely laminated or homogeneous mud over the buried peats, are consistent with the depositional sequence predicted for tectonic subsidence (fig. 11). Specifically, the gradual accumulation of clay and silt, reflected in the mud horizons, demonstrates long-term deposition in low energy estuarine environments. These burial deposits demonstrate many low energy depositional cycles rather than one high energy depositional event. Rather than succumbing to catastrophic burial by storm or flood processes, i.e., brief submergence, the preexisting marsh development was either terminated or diminished by abrupt and persistent marsh subsidence relative to mean tidal level. Abrupt tectonic displacement provides an unique mechanism by which rapid and persistent marsh submergence could be produced in Alsea Bay.

MAGNITUDE OF VERTICAL DISPLACEMENT

The tectonic displacements needed to subside the high marsh surfaces to intertidal levels of barren tidal flats or colonizing marsh substrates are on the order of one meter in Alsea Bay (table 1). However, the apparent marsh transitions over the intervals 2-4 (usually low marsh to colonizing marsh/tidal flat) , and the transitions over the intervals 0-2 (predominantly high marsh to upper low marsh/high marsh) suggest much smaller vertical displacements, i.e., as little as 0.5 m (fig. 17; table 1). We note here that while the first horizon 1MT might indicate marsh surface burial, it lacks evidence of burial by abrupt coseismic subsidence, and so it is not included in average displacement estimates. Vertical displacement due to sediment compaction is assumed to be small compared to the coseismic subsidence displacement in Alsea Bay. This assumption is based on the relatively small changes in bulk density downcore, which are further decreased when normalized against percent inorganic content. Local settling might partially account for differences in horizon elevations over short distances (10's-100's m) but is not indicated over broader areas (kilometers) in the bay. However, the posibility of basin wide settling can not be addressed by the present core data in Alsea Bay.

The estimated vertical displacements for Alsea Bay are substantially smaller than those reported for Netarts Bay (1-1.5 m subsidence) in northwest Oregon (Darienzo and Peterson, 1989; table 4). On the other hand, the 0.5-1.0 m vertical displacements in Alsea Bay are apparently greater than those 50 km to the south in Siuslaw Bay, where there were minor or no significant breaks in peat development (Nelson, 1987).

The distances of the central Oregon coast from the trench (90-120 km; Peterson et al., 1986) would indicate positions near the upper plate zero isobase, based on coseismic displacements from other subduction zones (fig. 1 and 10). For example, coseismic coastal subsidence has recently occurred along the coasts of Japan (1944 and 1946), Southern Chile (1960), Alaska (1964) and Columbia (1979), each located between 100 km and 130 km from a subduction zone trench (Heaton and Hartzell, 1986; West and McCrumb, 1988). The coast to trench distances of several Cascadia marsh systems in Netarts, Alsea and Siuslaw Bays and their corresponding vertical displacements, as estimated from their marsh records (table 4), are compared in figure 24A,B. The resulting plot shows a potential trend between decreasing distance from the trench and decreasing magnitudes of vertical coastal displacement. An upper plate flexure line or isobath of zero displacement (Plafker and Kachadoorian, 1969) for the Cascadia margin is tentatively estimated to be approximately 90 km from the trench, assuming a coastline intercept at 44°-43.5° N (fig. 24A,B and fig. 25).

An additional test of the relative landfall position of the zero isobase flexure line, is provided by the trend of episodic relative uplift, which is assumed to occur during the period of aseismic strain accumulation (fig. 10). For example, the Willapa Bay buried wetlands, most distant from the trench, commonly reach and exceed supratidal elevations (forest soils, reported by Atwater, 1988) while, the buried marsh horizons of Alsea and Siuslaw Bays, nearest the trench, only reach uppermost intertidal elevations (high marsh) (table 4). Additional studies are underway to confirm the landfall of the proposed Cascadia upperplate zero isobase, and to search for independent evidence of upperplate deformation along the southern Oregon coast, south of 44°.

TSUNAMI DEPOSITS

The clearest evidence of abrupt tectonic subsidence in the Alsea Bay marsh is the catastrophic burial of the west-central marsh peats by the anomalous SCLs (fig. 16A,C). Landward directed marine surges carried beach and/or tidal flat sands at least 1.5 km eastward to the westernmost marsh site (21) and deposited thin sand-rich layers (SCLs) over marsh surfaces of the northern bay margin and along the north channel (figs. 20 and 21). The SCLs show no evidence of bioturbation or internal cross stratification. The SCL sands appear to have been deposited directly and rapidly out of turbulent suspension.

Although the SCLs thin with increasing distance up the bay, the thicker SCL's of the western marsh are generally formed on low marsh surfaces. This is shown by thick SCLs over peaty horizons with relatively low organic content and thus corresponding low paleo-tidal elevation (fig. 16A). In addition, the marine surges which flowed up the north channel were insufficient to cross over the narrow marsh at site 4 to supply this site with a significant beach sand component (fig. 21). We interpret these patterns of SCL deposition to indicate that marine surges flowed into the bay mouth and continued due east to the northeast bay margin, where they deposited sand and muddy sand over subsided marsh tops (2MT, 3MT, 5MT). The surges continued up the north channel but rapidly diminished in flow energy, depositing only thin, sandy mud or silty mud horizons in the central marsh sites. The apparent inundation of intertidal and/or supratidal bay lands (marsh surfaces) between sites 1 and 5 in the middle-upper estuarine reaches (figs. 2,5 and 13) would have greatly reduced the mass and associated momentum of the landward directed surges, thus attenuating the upchannel flow (A. Baptista, pers. comm., 1990).

As has been suggested for similar horizons in both southwest Washington (Atwater, 1987; Reinhart and Bourgeois, 1989), and in northwest Oregon (Grant and McLaren, 1987; Peterson et al., 1988; Darienzo and Peterson, 1990), these SCLs are most likely to have derived from tsunamis generated by local coseismic displacements of the upper plate. The observed SCL generation in Alsea Bay provides some important constraints on local tsunami deposition in the Cascadia margin. For example, the SCLs in the Alsea Bay marsh have similar ranges in tsunami deposit thickness (1-25 cm), as the tsunami deposits reported from tidal creek marshes of Willapa Bay, Washington (Atwater, 1988; Reinhart and Bourgeois, 1989) and from the lagoonal marsh of Netarts Bay, northern Oregon (Darienzo and Peterson, 1990). The similarity of tsunami deposit thickness between these bays occurs even though the Netarts and Willapa marshes demonstrate a factor of two to three times the vertical displacement (coseismic subsidence) as that estimated for Alsea Bay (table 4).

The small subsidence displacements in Alsea Bay, i.e., probably between 0.5 and 1 m in the upper 2-4 burial units (fig. 24), did not preclude the deposition and preservation of associated tsunami deposits in this marsh system. Although some SCLs do thicken over lower marsh settings, as previously described, the greatest variation in tsunami deposit thickness is controlled by the landward attenuation of the surges deflecting around lower basin shorelines and moving up the narrow tidal creek channels (figs. 16 and 21). The apparent independence between tsunami deposition and the magnitude of local, coseismic subsidence means that large, locally generated tsunamis should be capable of leaving distinct tsunami deposits on marsh and tidal flat settings that have experienced little or no corresponding coseismic subsidence. This proves to be a potentially significant point as discussed below.

As previously noted and shown in figure 16, the observed SCL deposits in Alsea Bay are only associated with events of marsh subsidence, apparently caused by coseismic plate deformation. A similar observation in Netarts Bay was used to infer that the preserved tsunami deposits there were produced by locally generated tsunamis, and not by distantly produced tsunamis from other Pacific rim margins (Peterson et al., 1988). Taking this approach a step further, it might be possible to use the correspondence between tsunami deposits and coseismic subsidence in a marsh record to test whether a tsunami was generated within a given segment of the Cascadia margin, as described below.

In a margin where different segments undergo dislocation at different times the displacement of adjacent segments could produce tsunamis that might leave distinctive deposits on marsh or tidal flat surfaces that did not undergo corresponding tectonic subsidence. This is to say, that the tsunami deposits might occur in vertical sequences that showed no evidence of corresponding coseismic subsidence. For example, such records of 'independent' tsunami deposits would be expected in Alsea Bay if small segments of the Cascadia margin, adjacent to the Alsea Bay region, released at times different than from those in the Alsea Bay region itself (fig. 26). However, the observed marsh records in Alsea Bay do not show such independent tsunami deposits. A nearly one to one correlation of SCL development and local marsh subsidence is recorded in the upper burial units (1-5) of the Alsea Bay marsh system (figure 16). This high correlation could imply a synchronous coseismic displacement over large areas, particularly if similar one to one correspondences of tsunami deposition and coastal subsidence are found in additional bays to the north (fig. 26).

CHRONOLOGY OF BURIAL EVENTS

Significantly, the youngest peat top coseismically subsided in Alsea Bay (MT2 horizon) has a radiocarbon age (480 RCYBP) that is consistent with radiocarbon ages of other youngest buried peats and forest soils reported for northern Oregon (Darienzo and Peterson, 1990) and Washington (Atwater, 1988). A more accurate age of the most recent event of coseismic subsidence in southwest Washington is provided by tree ring dates (approximately 1690 AD) of cedar snags killed by their submergence to intertidal levels (Yamagouchi et. al., 1989). Unfortunately, tree trunks suitable for tree ring dating have yet to be identified in buried peats of the Alsea Bay marsh.

The next youngest buried horizon in Alsea Bay (MT3) provides another intriguing date of 800 RCYBP (561-903 BP calibrated age). This is the first report of a coastal subsidence event in the central and northern Oregon coast to have occurred during this time period. Additional stratigraphic work is needed to establish whether this coastal subsidence event is widely recorded in other marsh systems of the Cascadia margin.

Recurrence intervals between successive subsidence events in Alsea Bay are found to range from as little 250 yr (MT9-MT8) to as much as 1,370 yr (MT10-MT9), based on corresponding, uncalibrated peat radiocarbon dates (fig. 22). Dating errors of up to several hundred years have been obtained from radiocarbon dating of individual Cascadia subsidence events (fig. 22; Atwater, 1988; Peterson and Darienzo, 1990; Grant et al., 1990). However the accuracy of estimating average recurrence intervals is increased over longer time periods as random errors cancel with the larger number of subsidence events. The average recurrence interval of the youngest three event intervals (MT5-MT2) from 1490 to 480 RCYBP is estimated to be about 340 years. By comparison, the average recurrence interval of the next three event intervals (MT8-MT5) from 2890 to 1490 RCYBP is estimated to be about 470 years. The average recurrence interval for the longest period of record 480 to 4510 RCYBP is estimated to be about 500 years for 8 events.

It is noteworthy that the long-term average recurrence interval in Alsea Bay, i.e., on the order of 500 years, is roughly the same as those reported for Willapa Bay (Atwater, 1988) and Netarts Bay (Peterson et al., 1988). The similarity of these average recurrence intervals from widely separated sites in Oregon and Washington supports the argument that the corresponding coseismic events are linked by regional megathrust mechanisms. By comparison, the average recurrence interval between seismic events recorded in the marshes (about 500 years) is similar to the average recurrence interval of turbidity flows (590 years) reported for submarine canyons of the Cascadia continental slope (Adams, 1990). However, we stress that average recurrence intervals measured over some shorter time spans in Alsea Bay imply substantially shorter recurrence intervals, such as 340 years for the MT5-MT2 time span. Further comparisons of onshore and offshore records of subduction zone paleoseismicity in the Cascadia margin are needed to validate these apparent differences in average recurrence intervals between seismic events.

CONCLUSIONS

(1) The broad correlation of key peaty horizons in the top two meters of the Alsea marsh and the similar nature of marsh burial sequences throughout the Alsea Bay estuary demonstrate an episodic, system-wide submergence and burial of preexisting marsh surfaces. Peat burial sequences in Alsea Bay do not reflect catastrophic burial by brief climatic or oceanographic events, but rather they demonstrate rapid and persistent subsidence followed by gradual suspension deposition and marsh emergence. Furthermore, historically extreme events of river floods, storm surges and tidal inlet changes in Alsea Bay have not produced changes in mean tidal level or range that are sufficient in either magnitude and/or duration to have significantly impacted modern marsh development.

(2) Coseismic subsidence is apparently the only mechanism capable of producing the observed records of episodic marsh burial in Alsea Bay. Specifically, the cyclic episodes of gradual coastal uplift and sedimentation followed by abrupt coastal subsidence at Alsea Bay reflect alternating periods of crustal strain accumulation (gradual) and strain release (abrupt) in an active tectonic setting. Comparisons of these vertical movements in Alsea Bay with other Cascadia marsh systems demonstrate potential trends in the sign and magnitude of vertical motions. The along-margin trends of decreasing tectonic subsidence and uplift with decreasing distance from the trench imply regional rather than local tectonic control of the observed coastal subsidence. These regional trends of tectonic coastal displacements are consistent with upperplate flexure in a strongly coupled subduction zone. Furthermore,

they possibly indicate the relative position of an upperplate flexure line or zero isobase intersecting the Oregon coast near 44° N latitude.

(3) Coseismic subsidence of the preexisting marsh surfaces in Alsea Bay are indicated by several independent lines of evidence for contemporaneous tsunami deposition. Proposed tsunami deposits (SCLs) above buried marsh surfaces are anomalously sand rich. In addition, they contain elevated abundances of marine source sand relative to adjacent tidal flat or riverine-channel deposits. Both the relative thickness and heavy mineral content of the SCLs demonstrate landward-directed attenuation of marine surge transport. Although the SCLs inevitably lie directly above subsided peats, the minimal magnitude of estimated subsidence in Alsea Bay did not preclude their deposition or preservation. A nearly one to one correlation between tsunami deposition and coastal subsidence recorded in the upper four burial units from Alsea Bay might indicate synchronous coseismic displacements over substantial lengths of the central Oregon margin.

(4) We find that the age of the most recent event of coseismic subsidence at Alsea Bay (480 RCYBP) is consistent with reported ages of the most recent coseismic subsidence at other Cascadia marsh systems in Oregon and Washington. However, additional work is needed to establish whether this most recent event and/or other burial events in Alsea Bay are synchronous with coseismic subsidence events in Washington and northern Oregon. Average recurrence intervals between at least 3 successive events in Alsea Bay are estimated to be as little as 340 years (three events during 1,490-480 RCYBP). By comparison, an average recurrence interval of 500 years, estimated for the longest period of record (4,510-480 RCYBP) in Alsea Bay is similar to long-term recurrence intervals (500 years) reported from other Cascadia marsh systems.

ACKNOWLEDGEMENTS

We thank Henry Pittock for providing records of wind speed, atmospheric pressure and corresponding storm surge levels from Yaquina Bay, Oregon. We appreciate the time Alan Nelson spent in showing us the marsh stratigraphy in Siuslaw Bay, Oregon. Charles Clough assisted with surveys and lateral correlations of buried peats in cut banks of Alsea Bay. Larry Kauffman provided us with a boat, motor and dock facility for the extensive coring and surveying of the Alsea Bay marsh. Margaret Mumford and Carolyn Peterson produced many of the line drawings used in this manuscript. We thank Wendy Grant and Jim Phipps for reviewing this manuscript and providing many suggestions for its improvement. This research was supported by the U.S. Geological Survey, under the National Earthquake Hazards Reduction Program, Grant Number 14-08-0001-G1512 and by the National Science Foundation, Grant EAR-8903903.

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TABLE 1 TIDAL LEVELS AND MARSH ELEVATIONS IN ALSEA BAY

Tidal Stages	Elevation (m)
MHHW	1.01
MHW	0.80
MTL	0.00
MLW	-0.08
MLLW	-1.01

Marsh Types	Elevations (m) MTL	Key Plant Assemblages
High Marsh	1.4-1.8	High Marsh:
Transitional Marsh	1.4-1.1	*Deschampsia caespitosa*
Low Marsh	0.6-1.1	*Juncus sp.*
Colonizing Marsh	0.3-0.6	*Potentilla pacifica*
Tidal Flat	0.4-0.6	*Grindelia integrifolia*
		Low Marsh:
		Salicornia virginica
		Triglochin maritimum

Core Site Elevations

Sites	Elevations (m) MTL	Sites	Elevations (m) MTL
2, 3	1.4	12*	1.5
4	1.8 (channel levee)	13*	1.6
6*	1.5	16	1.4
7	1.6	17	1.7
8	1.5	18	1.6
9, 14	1.5	19	1.5
10	1.6	20	1.5
11	1.4	21*	1.5

* Core site elevations (accuracy ± 0.3 m) estimated from adjacent core sites and long distance sightings with transit. All other core site elevations (accuracy ± 0.1 m) are taken from direct leveling surveys of shorter distances (maximum 500 m distance between survey sites). Tidal stages are based on tide gauge records from the Drift Creek Station established 1976-1977 by NOAA. Key plant assemblages are based on Jefferson (1975) as well as our own observations.

TABLE 2 ANALYSES OF ALSEA BAY MARSH CORES

Core/Horizon	Depth (m) MTL	Density (g/cc)	Organics %	Sand %	Silt&Clay %
Core Site 21					
Surface	1.50				
0MT	1.46	0.28	29.0	10.8	89.2
0MB	1.40		34.4	13.0	87.0
1MT	1.34	0.42	41.1	13.0	87.0
1MB	1.25		41.8	12.1	87.9
1SCL	1.18			76.9	23.1
2MT	1.06		32.2	8.9	91.1
2MB	1.00		10.0	40.0	60.0
2SCL	0.75	1.47		88.5	11.5
3RMT	0.63	0.65	7.9	10.8	89.2
3RMB	0.41		5.7	0.3	99.7
3SCL	0.35			58.1	41.9
5MT	0.32	0.53	9.9	0.7	99.3
5S	0.06		6.0	4.1	95.9
5SCL	-0.37			81.8	18.2
6MT	-0.41	0.52	13.0	0.9	99.1
6S	-0.65		5.3	1.1	98.9
Core Site 8					
Surface	1.50				
0MT	1.49		43.7	2.2	97.8
0MB	1.43		40.0	6.7	93.3
1MT	1.35	0.23	37.6	0.9	99.1
1MB	1.18		37.5	1.8	98.2
2MT	1.10	0.26	48.2	0.3	99.7
2MB	0.74		12.2	20.8	79.2
3MT	0.55		17.1	2.3	97.7
3MB	0.38		14.0	1.0	99.0
4MT	0.19	0.29	13.8	0.2	99.8
4S	-0.12		6.9	1.9	98.1
5MT	-0.23	0.47	27.6	0.5	99.5
5S	-0.97	0.85	4.3	58.4	41.6
6MT	-1.10	0.53	12.2	5.3	94.7
6S	-1.96		6.9	6.8	93.2
7MT	-2.12	0.42	23.7	0.9	99.1
7MB	-2.62		10.3	0.8	99.2
8MT	-2.82		30.9	1.2	98.8
8MB	-2.86		16.4	1.1	98.9
9MT	-3.00	0.33	32.9	4.2	95.8
9S	-4.94		7.7	12.4	87.6
10MT	-5.22	0.41	23.9	0.6	99.4

TABLE 2 ANALYSES OF ALSEA BAY MARSH CORES (CONTINUED)

Core/Horizon	Depth (m) MTL	Density (g/cc)	Organics %	Sand %	Silt&Clay %
Core Site 12					
Surface	1.50				
0MT	1.46		32.1	2.0	98.0
0MB	1.37		26.6	5.1	94.9
1MT	1.28	0.30	37.2	5.1	94.9
1MB	1.01		24.1	4.8	95.2
2MT	0.94	0.31	30.2	0.8	99.2
2S	0.46		6.3	12.5	87.5
3MT	0.38		15.4	7.6	92.4
3S	0.32		9.0	32.3	67.7
4MT	0.27	0.37	12.4	5.7	94.3
4S	0.03	0.90	7.0	68.5	31.5

Table 2 Key: MT=Marsh (peat) top
MB=Marsh (Peat) Bottom
S=Very Low Organic Sediments
SCL=Sediment Capping Layer

TABLE 3. MINERALOGY OF SEDIMENT CAPPING LAYERS IN ALSEA BAY MARSH

Horizon	Relative Abundance of Beach Sand Component (%)			
	Site 21	Site 15	Site 19	*Site12
1SCL	21	16	12	00
2MT	07	10	00	00
2SCL	47	31	09	00
3MT	10	07	00	00
4SCL	27	14	04	00
5MT	05	00	00	00

* Base of burial units (S) in site 12 are used to represent equivalent stratigraphic positions to SCLs from the lower bay sites.

TABLE 4. MINIMUM SUBSIDENCE ESTIMATED FOR THE FOUR MOST RECENT SUBMERGENCE EVENTS IN SELECTED CASCADIA TIDAL BASINS

Tidal Basin	Netarts	Alsea	Siuslaw
Event 1			
Sequence	VHM-TF	HM-HM	M-M
Displacement (m)	1.5	0.5	0-0.5
Event 2			
Sequence	HM-TF	HM-LM	
Displacement (m)	1-1.5	0.5-1	
Event 3			
Sequence	HM-TF	LM-TF	
Displacement (m)	1-1.5	0.5-1	
Event 4			
Sequence	VHM-TF	LM-TF	
Displacement (m)	1.5	0.5-1	
Average Range of Displacement (m)	1-1.5	0.5-1	0-0.5

Key to Modern Elevations
Forest (FS)
Very High Marsh (VHM)
High Marsh (HM)
Low Marsh (LM)
Marsh Undefined (M)
Tidal Flat (TF)

Survey data for Alsea Bay (table 1; figure 14), for Netarts Bay (Darienzo and Peterson, 1989), and for Siuslaw Bay (Nelson, 1987; we assume minimum to no subsidence). Note that we do not imply any temporal correlation between the youngest four burial events in these bays for this table.

APPENDIX 1 STRATIGRAPHIC SECTION MEASUREMENTS OF SHALLOW PEATY HORIZONS IN CUT BANKS OF ALSEA BAY MARSH

DEPTH OF BURIED PEATY HORIZONS MEASURED IN CENTIMETERS BELOW SURFACE OF MODERN MARSH AT CORRESPONDING STATIONS

Station Number*	Depth (cm) of Upper Buried Peat	Depth (cm) of Lower Buried Peat
01	40	76
02	58	87
03	90	120
04	50	85
05	eroded	87
06	eroded	81
07	eroded	75
08	50	90
09	67	100
10	86	120
11	82	113
12	95	128
13	57	100
14	64	110
15	66	97
16	80	100
17	73	110
18	77	104
19	75	105
20	59	87
21	60	98
22	58	95
23	41	80
24	76	114
25	62	94
26	74	102
27	66	89
28	73	107
29	55	81
30	54	94
31	56	97
32	36	79
33	38	89
34	41	87
35	46	91
36	51	89
37	56	90
38	62	99
39	65	101
40	51	93
41	54	97
42	58	96
43	32	71
44	68	99
45	55	92
46	69	98

APPENDIX 1 STRATIGRAPHIC SECTION MEASUREMENTS OF SHALLOW PEATY HORIZONS IN CUT BANKS OF ALSEA BAY MARSH (CONTINUED)

DEPTH OF BURIED PEATY HORIZONS MEASURED IN CENTIMETERS BELOW SURFACE OF MODERN MARSH AT CORRESPONDING STATIONS

Station Number*	Depth (cm) of Upper Buried Peat	Depth (cm) of Lower Buried Peat
47	54	92
48	50	85
49	52	88
50	49	83
51	53	81
52	53	86
53	62	101
54	56	89
55	69	101
56	65	97
57	69	103
58	53	90
59	59	100
60	63	103
61	57	100
62	68	104

*See figure 12 for location of stratigraphic section stations in Alsea Bay Marsh

FIGURE CAPTIONS

Figure 1. Location map of the study area, Alsea Bay, (large solid circle) and several other wetland or marsh sites reported to record coastal submergence (small solid circles). The dashed line represents the estimated position of the sediment filled trench between the subducting Juan de Fuca plate and the overriding North American plate. The black arrows represent approximate directions of relative plate movement (after Riddihough, 1984).

Figure 2. Map of the Alsea Bay estuary, including (1) the barrier sand spit (just north of the tidal inlet), (2) the major fluvial source (Alsea River), (3) the contours of mean low low water outlining the north and south tidal channels (dashed lines), and (4) the fringing marsh system (plant symbols). Over 90 percent of the sediments flooring this high gradient, fluvially dominated estuary are in the sand size range. The bay is roughly divided on the basis of sand source into (1) the marine dominated lower reaches, (2) the fluvially dominated upper reaches, and (3) the transitional middle reaches (after Peterson et al., 1982).

Figure 3. Generalized profile of an estuary bottom showing the relations between substrate, plant communities and tidal elevation. Salt marshes occupy a narrow tidal elevation range between upland and tidal flat environments, making them ideal indicators of relative sea level. Figure from Oregon Estuaries, Division of State Lands, State of Oregon, 1973.

Figure 4. Diagram of a hypothetical, marsh vertical sequence developed within a tidal creek meander bend. Horizons in the stratigraphic column (right) correspond to depositional surfaces in the channel cross section (left). The resulting vertical sequence is produced as the channel migrates laterally, i.e., cutting the left bank and building the right bank, as shown in this figure.

Figure 5. Oblique aerial photograph (sighting due east) of the upper estuarine reaches of Alsea Bay and of the corresponding central and eastern marsh areas. See figure 2 for plan view of the estuary. Photograph taken by P. Komar.

Figure 6. Hypothetical river flood deposit with proximal and distal stratigraphic columns showing expected fining-up sequences at marsh levee and backmarsh positions, respectively. Riverine-tidal channels in most of the high-gradient estuaries of the Pacific Northwest are floored by sand and/or gravel, providing proximal sources of coarse grained sediments to channel margin environments during catastrophic floods.

Figure 7. Historical extreme event of ocean set-up from a storm surge in Yaquina Bay, located 15 km north of Alsea Bay, during November 13, 1981. Measured tidal level, wind velocity and atmospheric pressure were recorded simultaneously at the Hatfield Marine Science Center, Yaquina Bay, Oregon (H. Pittock, unpublished data). Measured tide level (small solid circles) ranges from 0.5 to 1 m above predicted tidal level (four large solid circles) during the maximum period of northeast to easterly directed wind stress (0-8 hrs, Nov. 14). Yaquina bay is roughly similar to Alsea Bay in size and morphology, but a larger tidal entrance in Yaquina Bay probably enhances storm set-up there relative to Alsea Bay.

Figure 8. Monthly mean sea level (dashed line) in centimeter readings from Yaquina Bay tide gauge for the 1982-83 El Nino Southern Oscillation (ENSO) period, and corresponding 10 year averages of monthly mean sea level (solid line) for the 1971-1981 decade (after Huyer et al., 1983). The measured increase of monthly mean sea level peaked at greater than 30 cm above normal for the duration of the 1983 winter, representing a historical extreme event of intraannual, elevated sea level.

Figure 9. Hypothetical storm deposits comprised of cyclic vertical sequences of sand and silt burying marsh horizons (see figure 4 or 6 for key to sediment types). Waning storm conditions might produce fining-up sequences, while variable ocean set-up and tidal cycles might produce more complex layering of sand and silt. The burial of successive supratidal marsh horizons by storm resuspension and deposition would require catastrophic storm events superimposed on a longer-term trend of coastal submergence.

Figure 10. Diagram of vertical coastal tectonics associated with (1) coupled strain accumulation and (2) coseismic shear dislocation between a subducting oceanic plate and an overriding continental plate (after Ando and Balazs, 1979). The relative position of coastline and the upperplate flexure line or zero isobase (Plafker and Kachadoorian, 1969) determines the direction of coastal tectonic displacement during alternating periods of aseismic strain accumulation and coseismic dislocation.

Figure 11. Hypothetical subsidence deposit including a fining-up vertical sequence of sand to mud and colonizing marsh above the buried pre-existing marsh surface. Sand and mud ratios in basal, lower intertidal layers might vary between sites as a function of local sediment supply and resuspension energy. However, the upper intertidal to supratidal layers should become increasingly rich in mud and organic material as the depositional surface approaches the maximum reach of high tidal levels.

Figure 12. Map of cut bank exposures examined in Alsea Bay. Solid line represents continuous exposure of two buried peaty horizons. Stratigraphic sections were measured at 62 stations (numbers 1-62) as identified by black arrows.

Figure 13. Core site locations in Alsea Bay marsh system.

Figure 14. Photographs of two, buried peaty horizons from cut bank exposures in Alsea Bay marsh. Photographic sites are shown in figure 12 and include photograph A (upper left) South Channel northwest bank, photograph B (upper right) South Channel northeast bank, photograph C (lower left) North Channel northeast bank, and photograph C (lower right) North Channel northwest bank. Sandy layers (generally several centimeters thick) directly above peaty horizons are differentially eroded, yielding two shadowed slits that correspond to the two peat tops in photographs A,C, D. Coins mark the tops of the two buried peat horizons in photograph B.

Figure 15. Correlation of two, buried peat horizons in 62 measured sections from the central marsh island in Alsea Bay. Depths (cm) of the two buried peat tops, below the modern marsh surface, are plotted against stratigraphic station number around the central marsh island perimeter (total distance of 4.5 km). See figure 12 for stratigraphic station locations 1-62, and Appendix 1 for corresponding depth measurements.

Figure 16. Core logs and stratigraphic correlations of key peaty horizons in the Alsea Bay marsh system from transects of the western-central marsh (16A), central-eastern marsh (16B) and central marsh (north to south; 16C). A key to the sediment composition and contact relations is displayed at the bottom of figure 16A. Core top elevations and horizon depths are shown relative to mean tidal level (see table 1). Burial units are numbered from 0 to 10 in representative core sections from sites 21, 12 and 8. Additional quantitative analyses of selected horizons are listed in table 2.

Figure 17. Downcore plots of relative organic material abundance in peaty horizons (MT=marsh top, MB=marsh bottom) of the modern marsh (O) and four uppermost burial units (1-4) from three core sites, 21, 8 and 12 in Alsea Bay. The fourth burial unit (4) is not recorded at site 21. Core site locations are shown in figure 13. Measured elevations and additional quantitative data for these horizons are shown in table 2.

Figure 18. Downcore plots of relative sand abundance in top and bottom peaty horizons of the modern marsh and the four uppermost burial units from three core sites 21, 8 and 12 in Alsea Bay.

Figure 19. Downcore plot of relative sand abundance in peaty horizons and in anomalous (sand-rich) sediment capping layers (SCL) that directly overlie buried peaty horizons at core site 21 in Alsea Bay. Measured elevations of the SCLs are provided in table 2.

Figure 20. Downcore plot of relative abundances of beach source component in analyzed sand fractions (0.06-0.25 micron size fraction) from SCL and marsh top horizons from four core sites 21, 15, 19 and 12 in Alsea Bay. Beach source components and river source components total 100 percent by volume abundance. The measured elevations of SCL and marsh top horizons are shown in table 2 and figure 16.

Figure 21. Map of percent beach sand component in modern estuarine sediments (contours at 10% intervals) and in 2SCL from core sites 21, 15, 19 and 12 progressing up the north channel of Alsea Bay. Black arrows show inferred landward direction of marine surge. The sand mineralogy for the 2SCL at site 18 (south channel) reflected a proximal river channel source and was not sufficient to discriminate transport direction. See figure 13 for numbered core site locations.

Figure 22. Core log and radiocarbon ages from core site 9 and one detrital wood fragment at stratigraphic station 41 in Alsea Bay. Radiocarbon dating was performed by Beta Analytic Inc. (beta#). Peat ages are shown in (1) radiocarbon years before present (RCYBP, one standard deviation), (2) ^{13}C adjusted age (C13 adj) based on measured sample $^{12}C/^{13}C$ ratios, and (3) calibrated age (cal. BP) based on sample two standard deviations about ^{14}C calibration curves established from tree-ring dating (Stuiver and Reimer, 1986). The peat tops, used for radiocarbon dating, predate the associated marsh submergence and burial, and so possibly over estimate the age of the subsidence events.

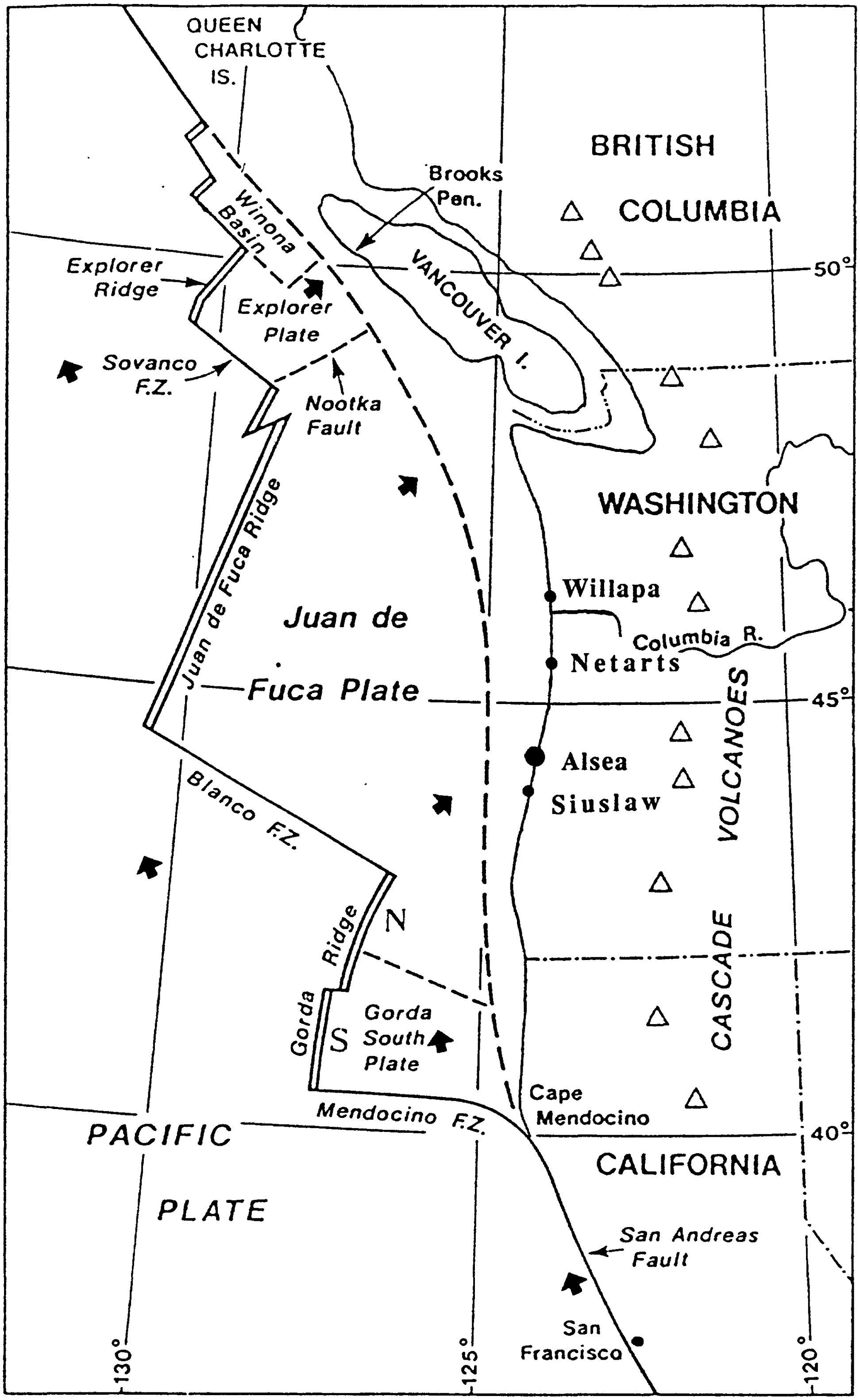
Figure 23. Changes in cross-sectional area of Alsea Bay inlet between 1985 and 1989. Graph shows changes in inlet shape and tidal inlet cross-sectional area during corresponding years (from Peterson et al., 1990).

Figure 24. Plots of estimated range in minimum coastal subsidence versus coastal latitude (24A) and the distance between coast and trench (24B) from three localities, including from south to north, Siuslaw, Alsea, and Netarts Bays. See table 4 for basis of subsidence magnitude estimates.

Figure 25. Diagram of predicted, upperplate flexure line or zero isobase position based on assumed trench parallel orientation and coastal interception between 44° and 43.5° N latitude (see fig. 24A,B). Trench position (dashed line) in south-central margin is approximated from mapped base of slope (Peterson et al., 1986). Coastal tidal basins (6 named) containing late Holocene records of salt marsh/wetland submergence and burial are shown for reference.

Figure 26. Diagram of two hypothetical models of (1) segmented interplate dislocation and (2) unsegmented interplate dislocation and their corresponding predicted records of coastal subsidence and tsunami deposition. In the segmented model, tsunami generation occurs in the coseismic northern segment (or southern segment), but it propagates to the aseismic central segment, leaving tsunami deposits within marsh burial units of Alsea Bay. Such intra-unit tsunami deposits would not be associated with local coastal subsidence. In the unsegmented model, tsunami generation and coastal subsidence occur

simultaneously throughout the adjacent segments. Resulting tsunami deposits are only associated with the bottom of burial units, demonstrating contemporaneous coastal subsidence. The second model (unsegmented interplate dislocation) is favored for the Alsea Bay region due to the presence of tsunami deposits at the base of burial units but not within burial units.



QUEEN CHARLOTTE IS.
BRITISH
COLUMBIA
Brooks Pen.
Winona Basin
Explorer Ridge
Explorer Plate
VANCOUVER I.
50°
Sovanco F.Z.
Nootka Fault
WASHINGTON
Juan de Fuca Ridge
Juan de Fuca Plate
Willapa
Columbia R.
Netarts
45°
Alsea
Siuslaw
VOLCANOES
Blanco F.Z.
N
Gorda Ridge
CASCADE
Gorda South Plate
S
Cape Mendocino
Mendocino F.Z.
PACIFIC PLATE
40°
CALIFORNIA
San Andreas Fault
San Francisco
130°
125°
120°

Fig. 1

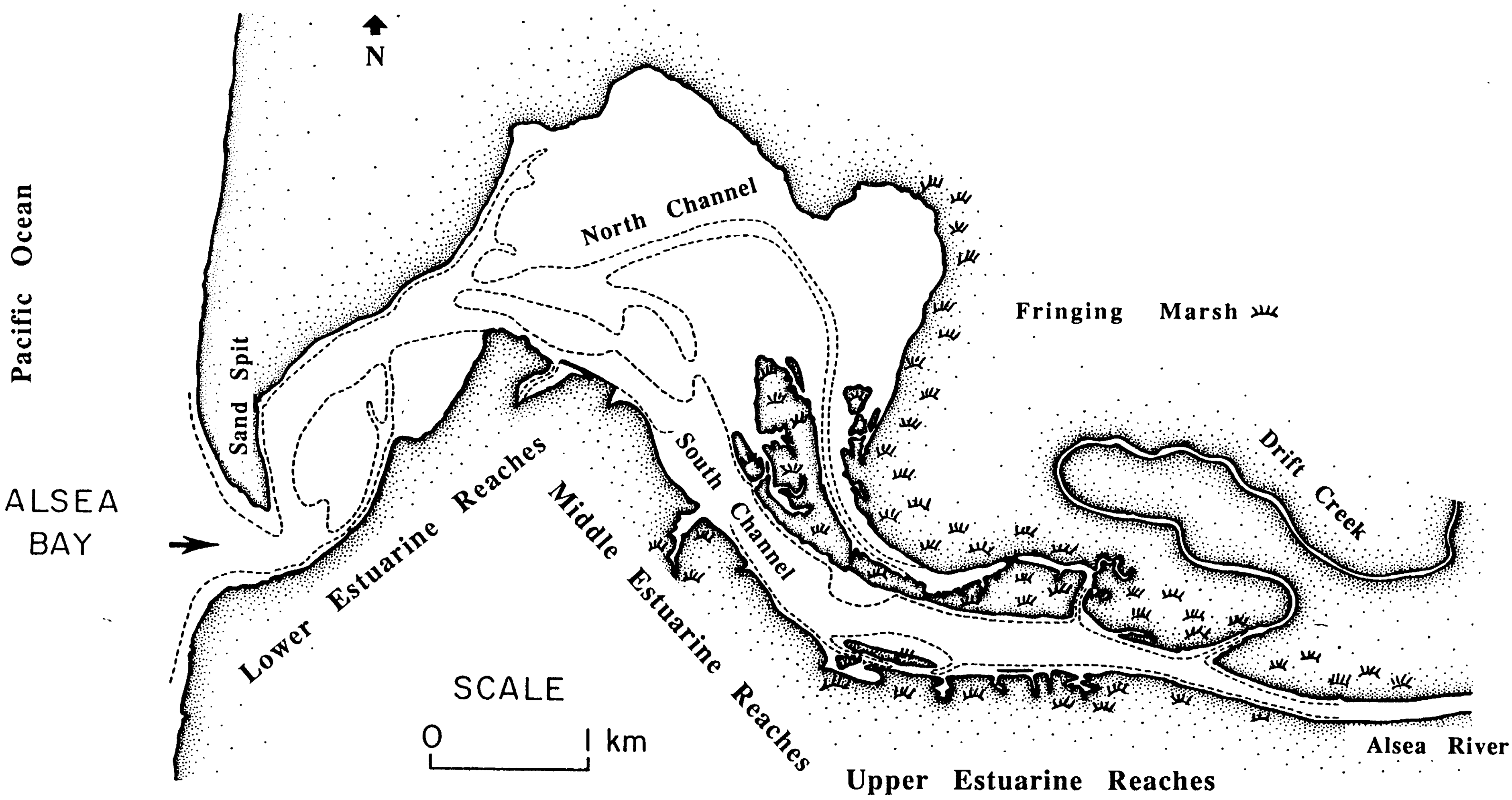

N
Pacific Ocean
ALSEA
BAY
Sand Spit
North Channel
South Channel
Fringing Marsh
Drift Creek
Lower Estuarine Reaches
Middle Estuarine Reaches
Upper Estuarine Reaches
Alsea River
SCALE
0
1 km

Fig. 2

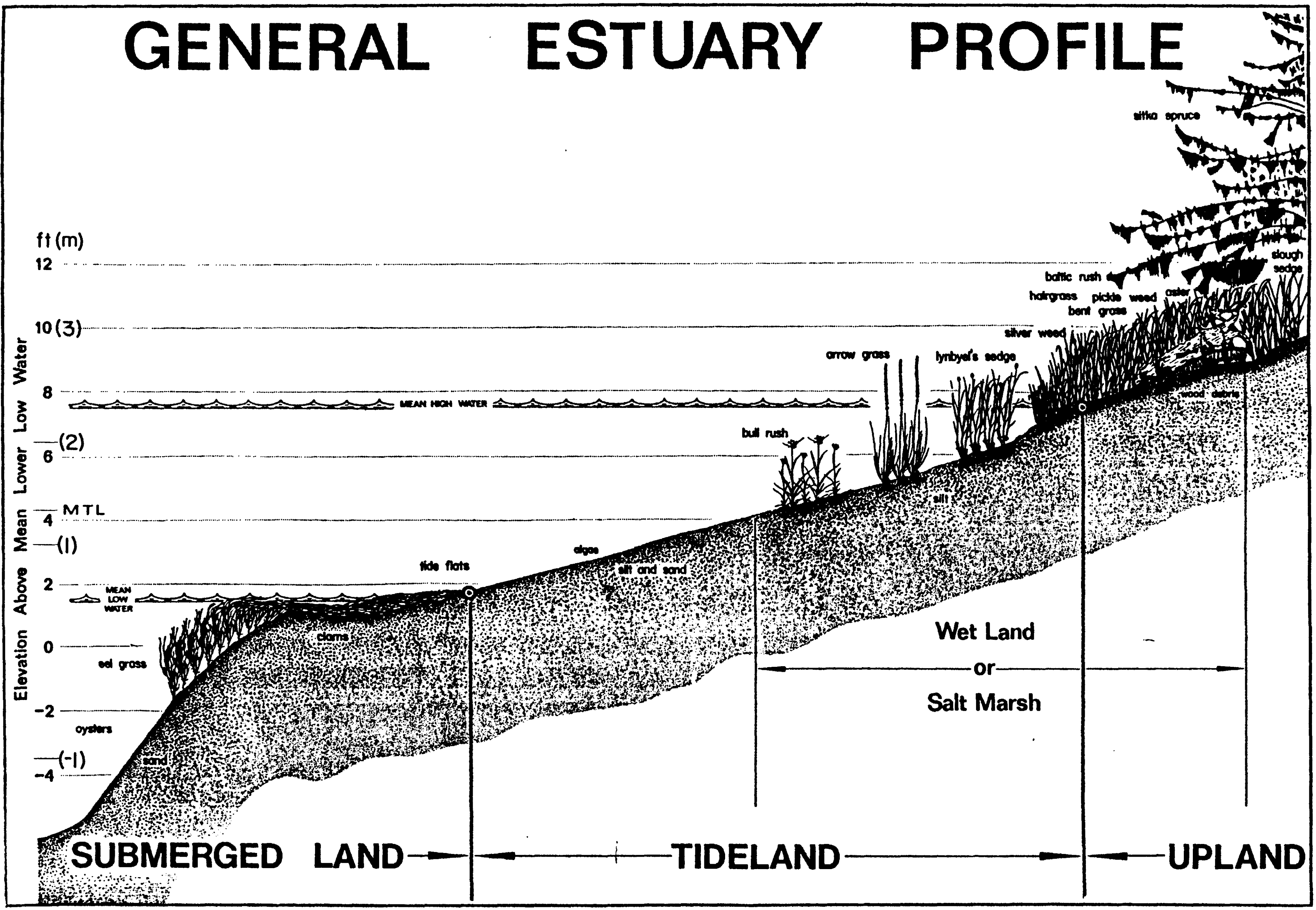

GENERAL ESTUARY PROFILE
ft (m)
12
10 (3)
8
(2)
6
MTL
4
(1)
2
0
-2
(-1)
-4
Elevation Above Mean Lower Low Water
MEAN HIGH WATER
MEAN LOW WATER
sitka spruce
slough sedge
baltic rush
hairgrass
pickle weed
aster
bent grass
silver weed
arrow grass
lynbyei's sedge
wood debris
bull rush
silt
algae
silt and sand
tide flats
clams
eel grass
oysters
sand
Wet Land
or
Salt Marsh
SUBMERGED LAND
TIDELAND
UPLAND

Fig. 3

Marsh Channel - Meander Deposit

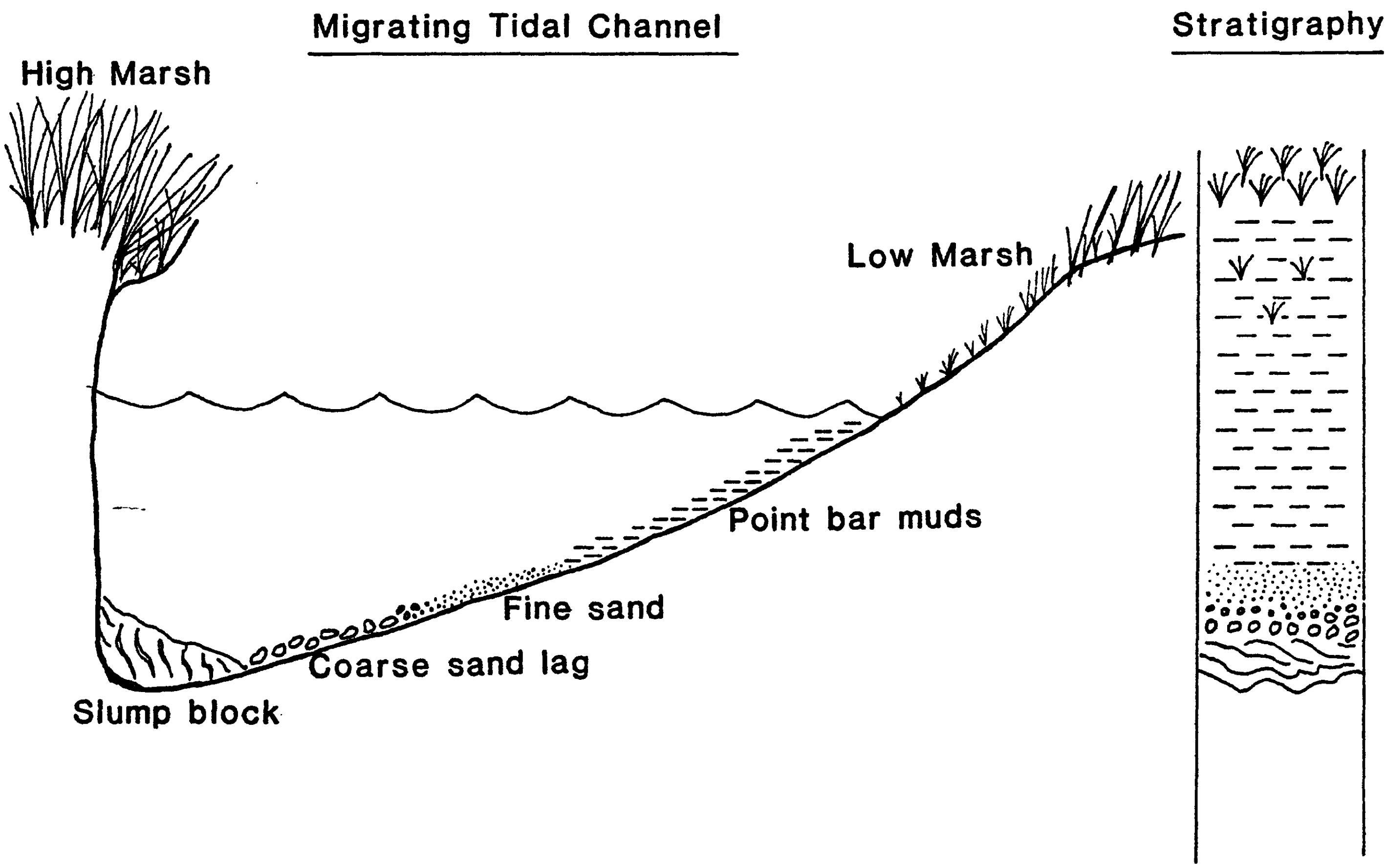


Fig. 4

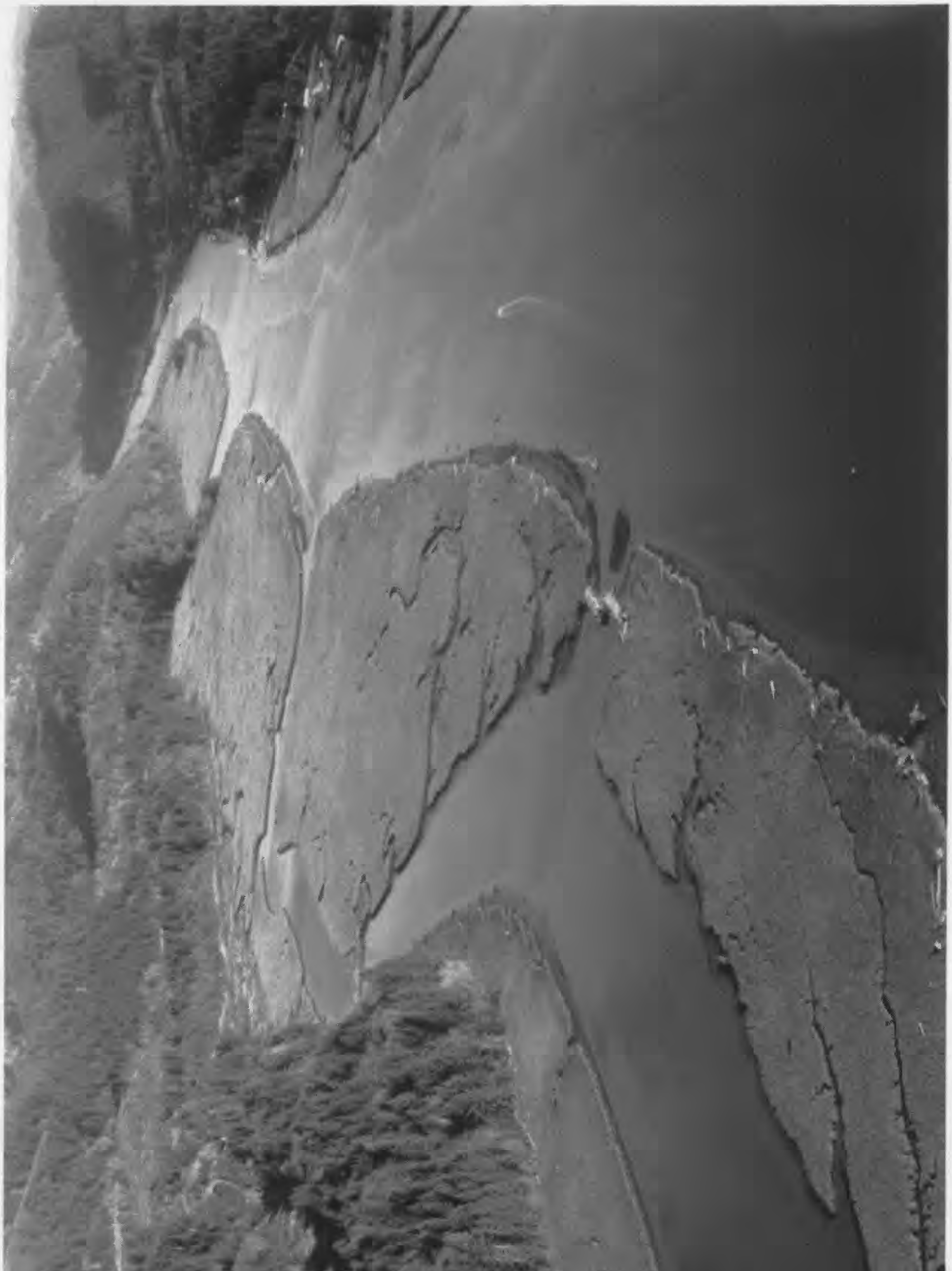


Fig. 5

River - Flood Deposit

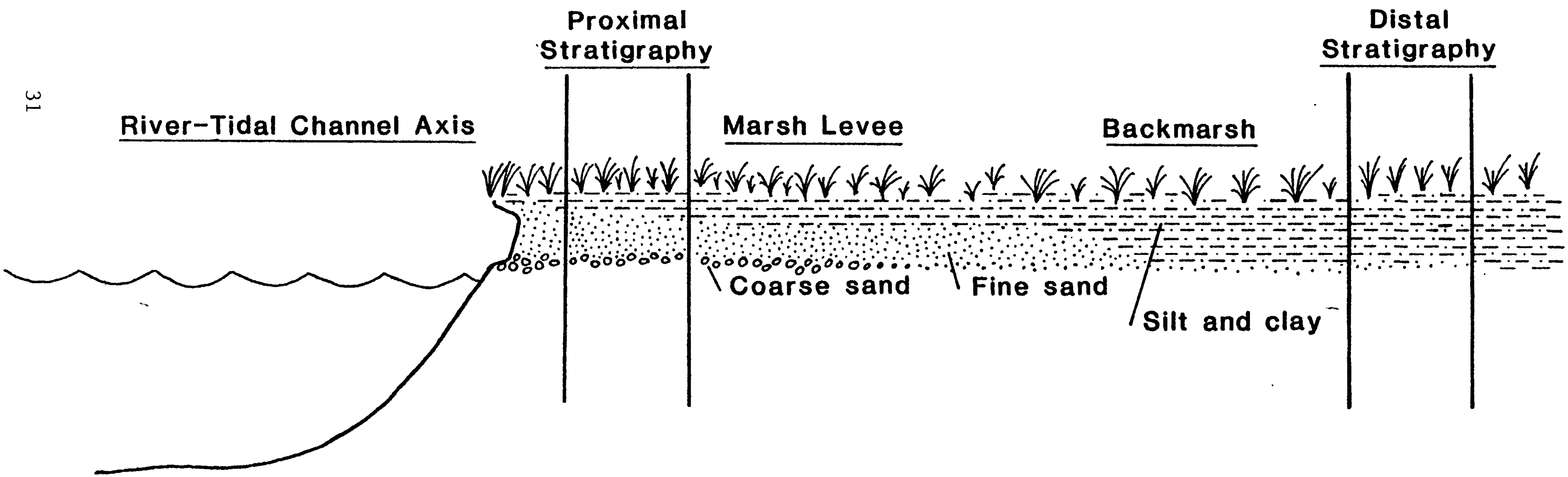


Fig. 6

Nov. 13-14, 1981 Yaquina Bay, Storm Surge

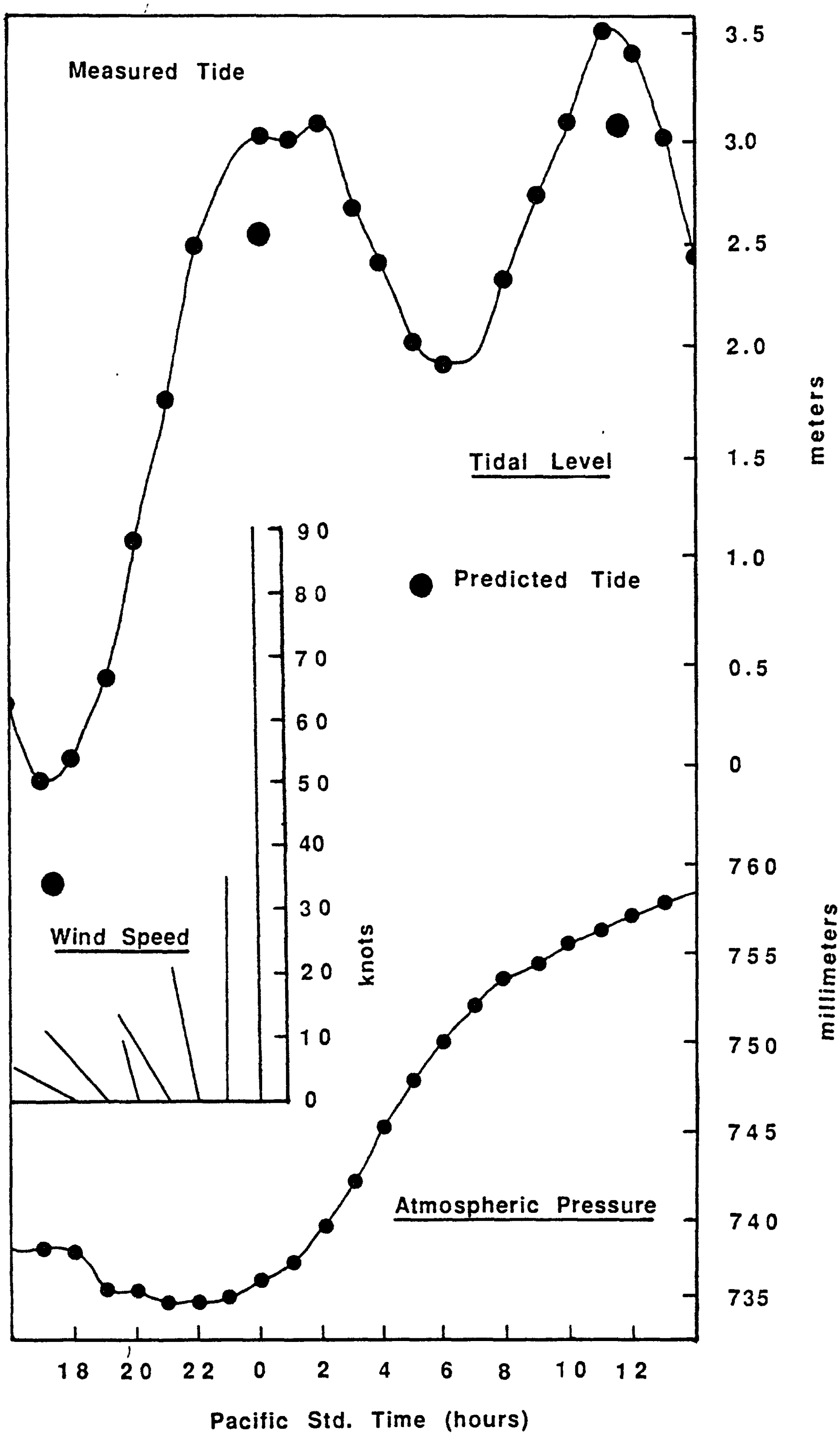


Fig. 7

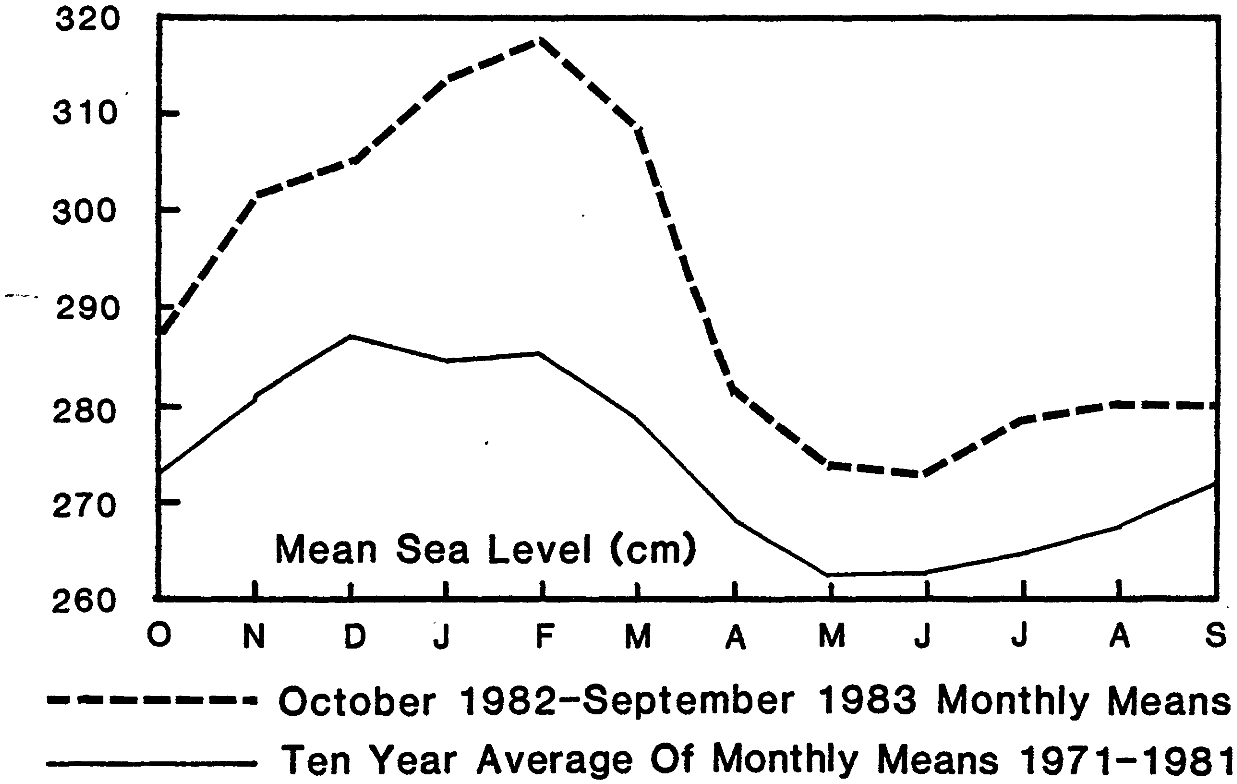

320
310
300
290
280
270
260
Mean Sea Level (cm)
O
N
D
J
F
M
A
M
J
J
A
S
October 1982–September 1983 Monthly Means
Ten Year Average Of Monthly Means 1971–1981

Fig. 8

Storm Resuspension Deposit

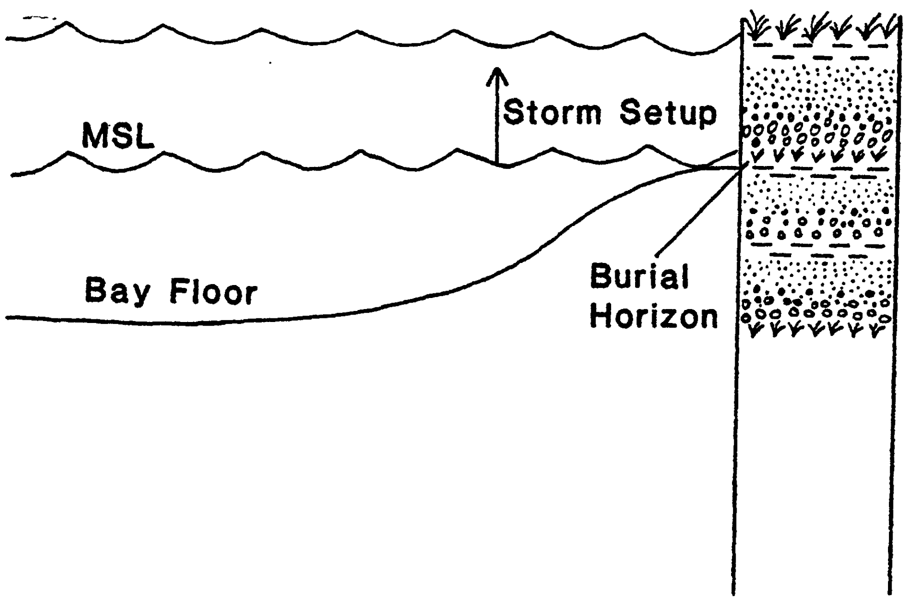


Fig. 9

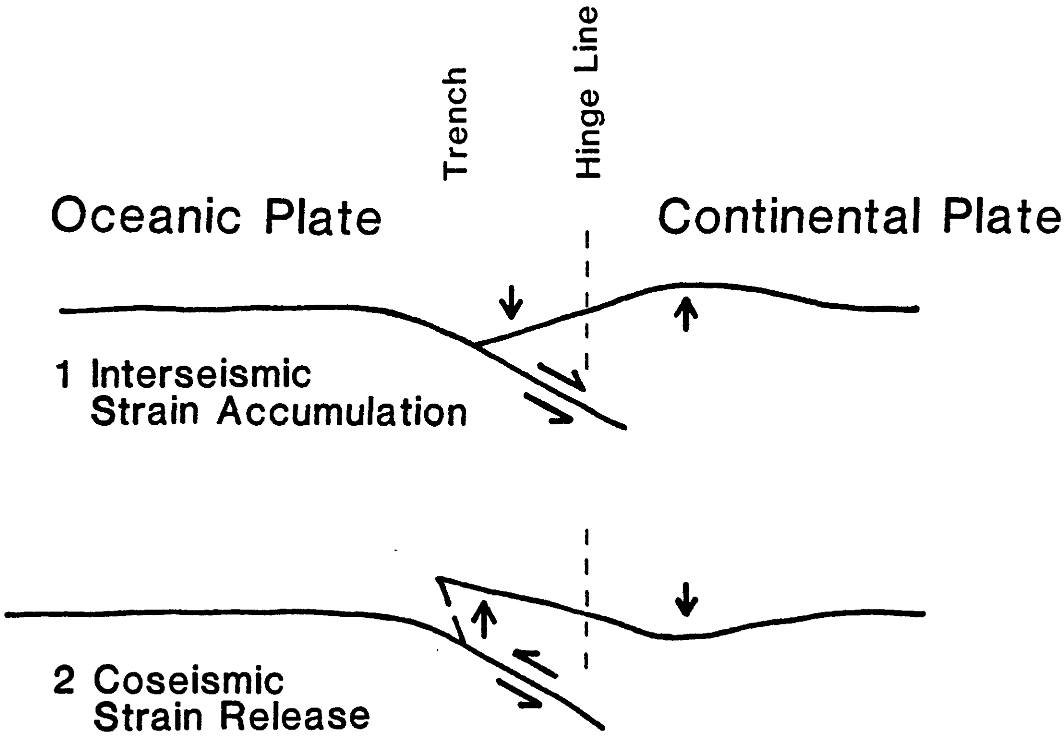

Trench
Hinge Line
Oceanic Plate
Continental Plate
1 Interseismic
Strain Accumulation
2 Coseismic
Strain Release

Fig. 10

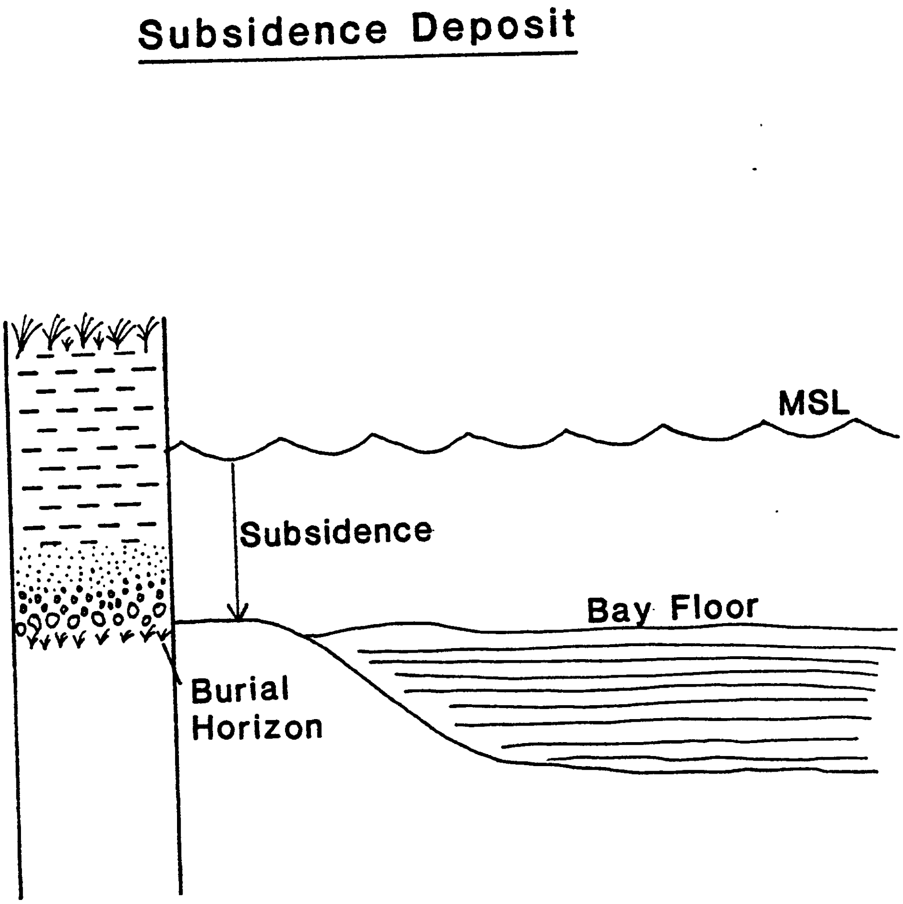

Subsidence Deposit
MSL
Subsidence
Bay Floor
Burial
Horizon

Fig. 11

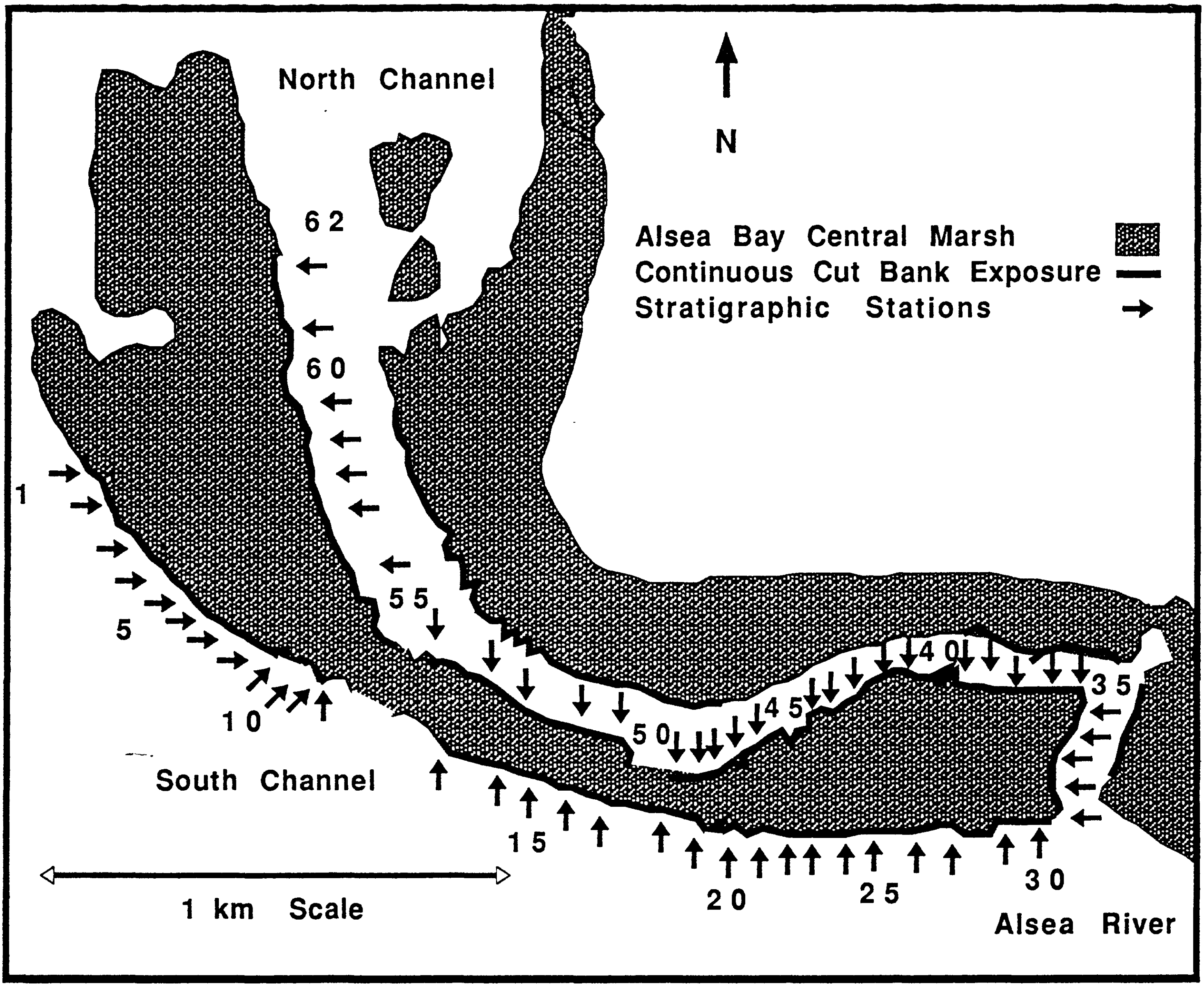

North Channel
N
Alsea Bay Central Marsh
Continuous Cut Bank Exposure
Stratigraphic Stations
62
60
1
5
10
55
50
45
40
35
30
25
20
15
South Channel
1 km Scale
Alsea River

Fig. 12

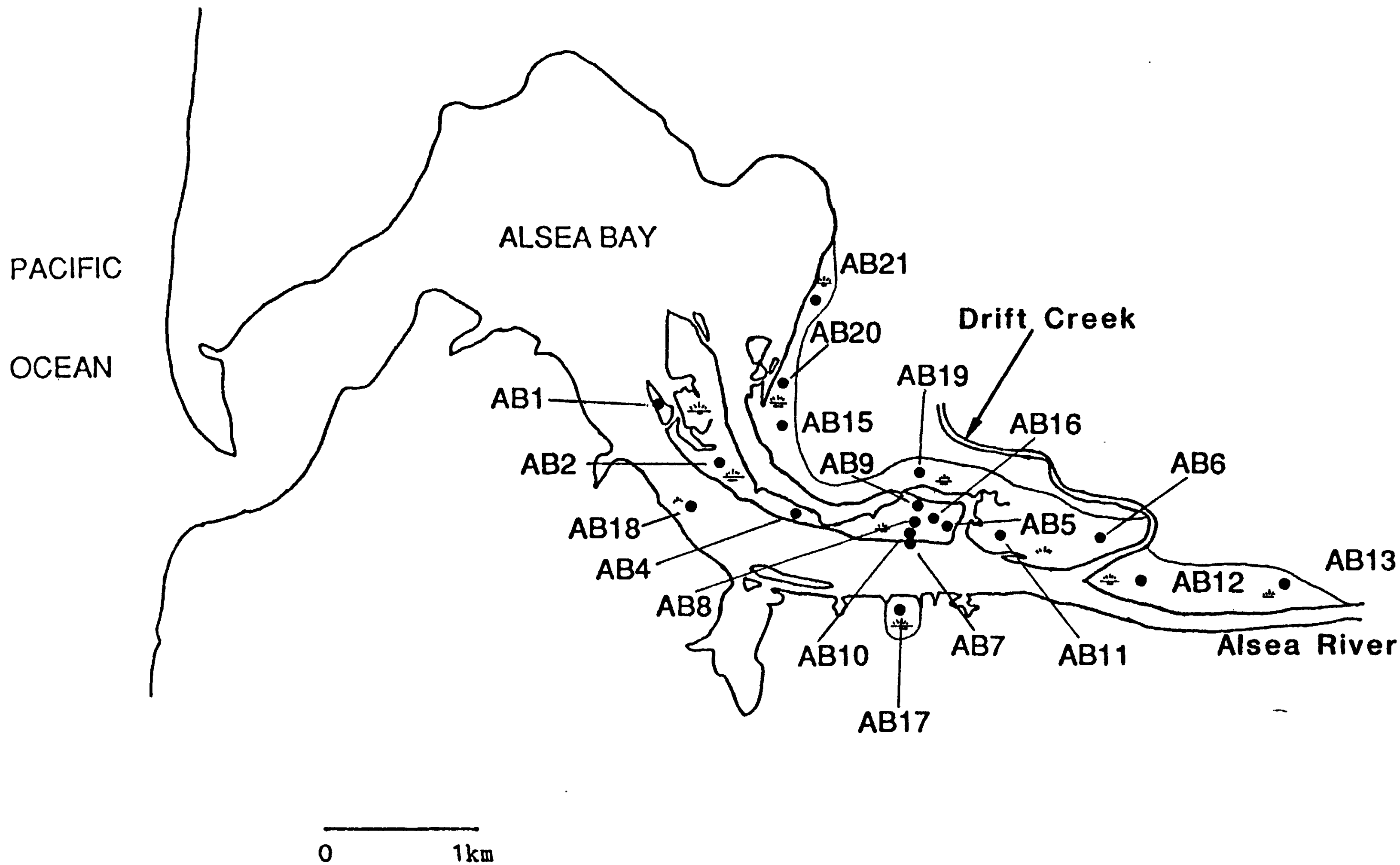

ALSEA BAY
PACIFIC
OCEAN
AB21
AB20
Drift Creek
AB19
AB1
AB15
AB16
AB2
AB9
AB6
AB18
AB5
AB13
AB4
AB12
AB8
AB10
AB7
AB11
Alsea River
AB17
0
1km

Fig. 13

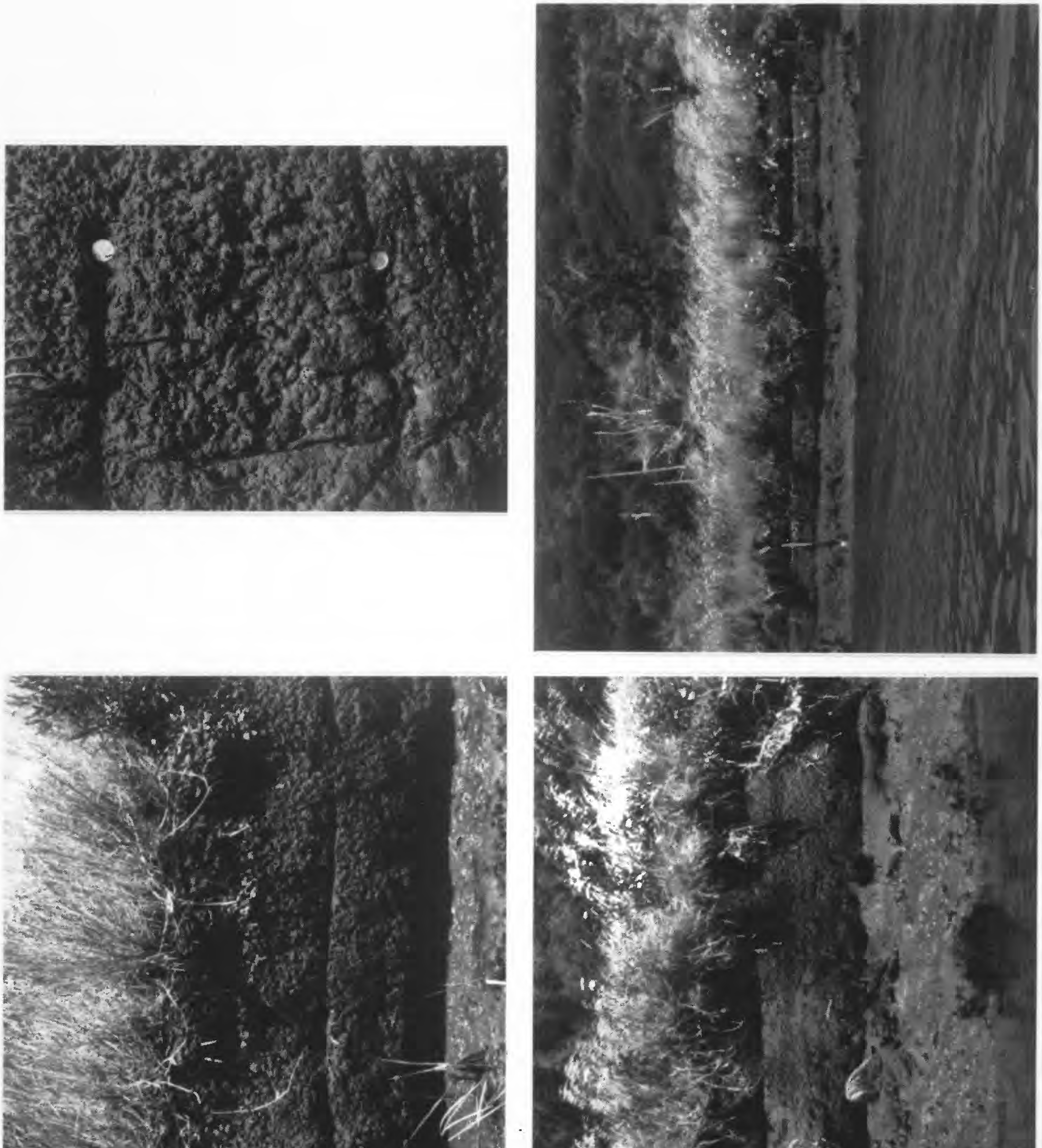


Fig. 14

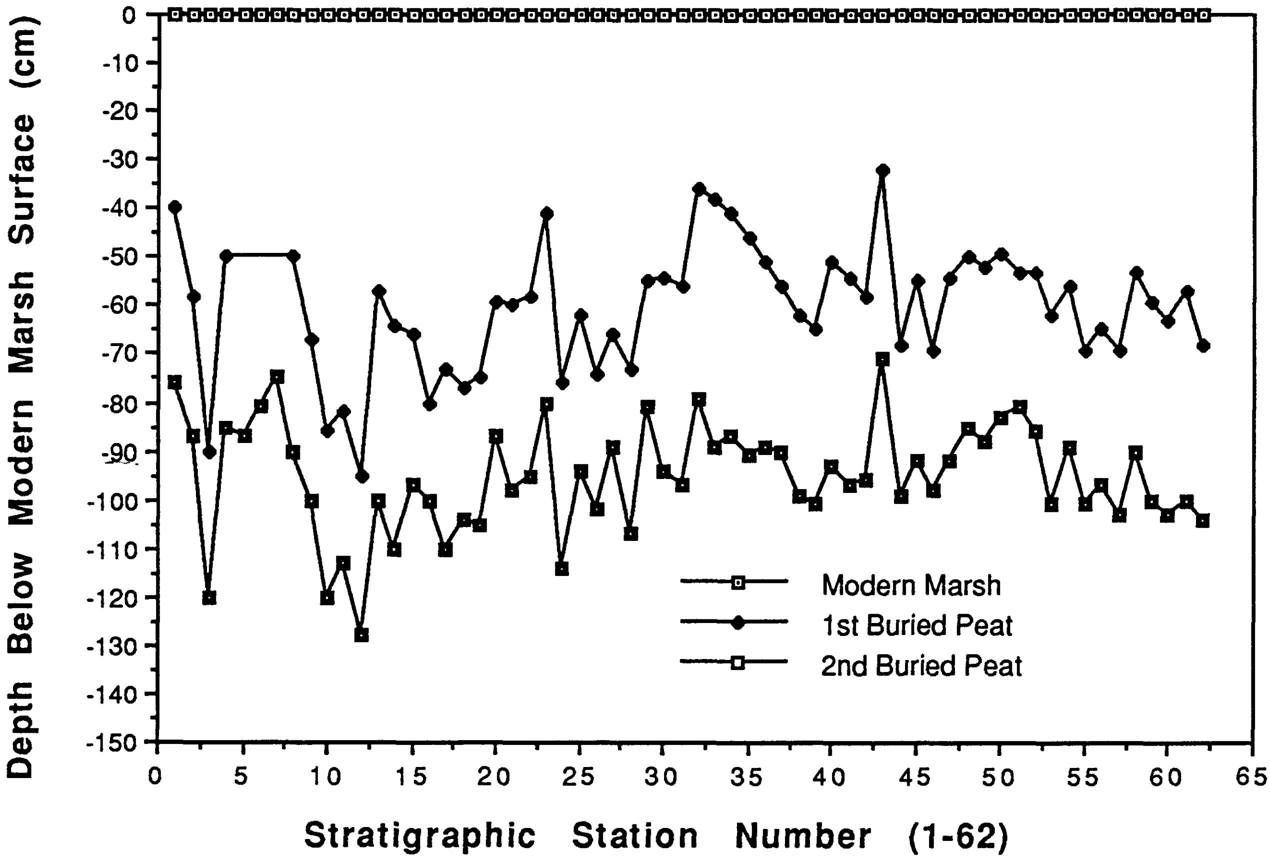

Depth Below Modern Marsh Surface (cm)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Stratigraphic Station Number (1-62)
Modern Marsh
1st Buried Peat
2nd Buried Peat

Fig. 15

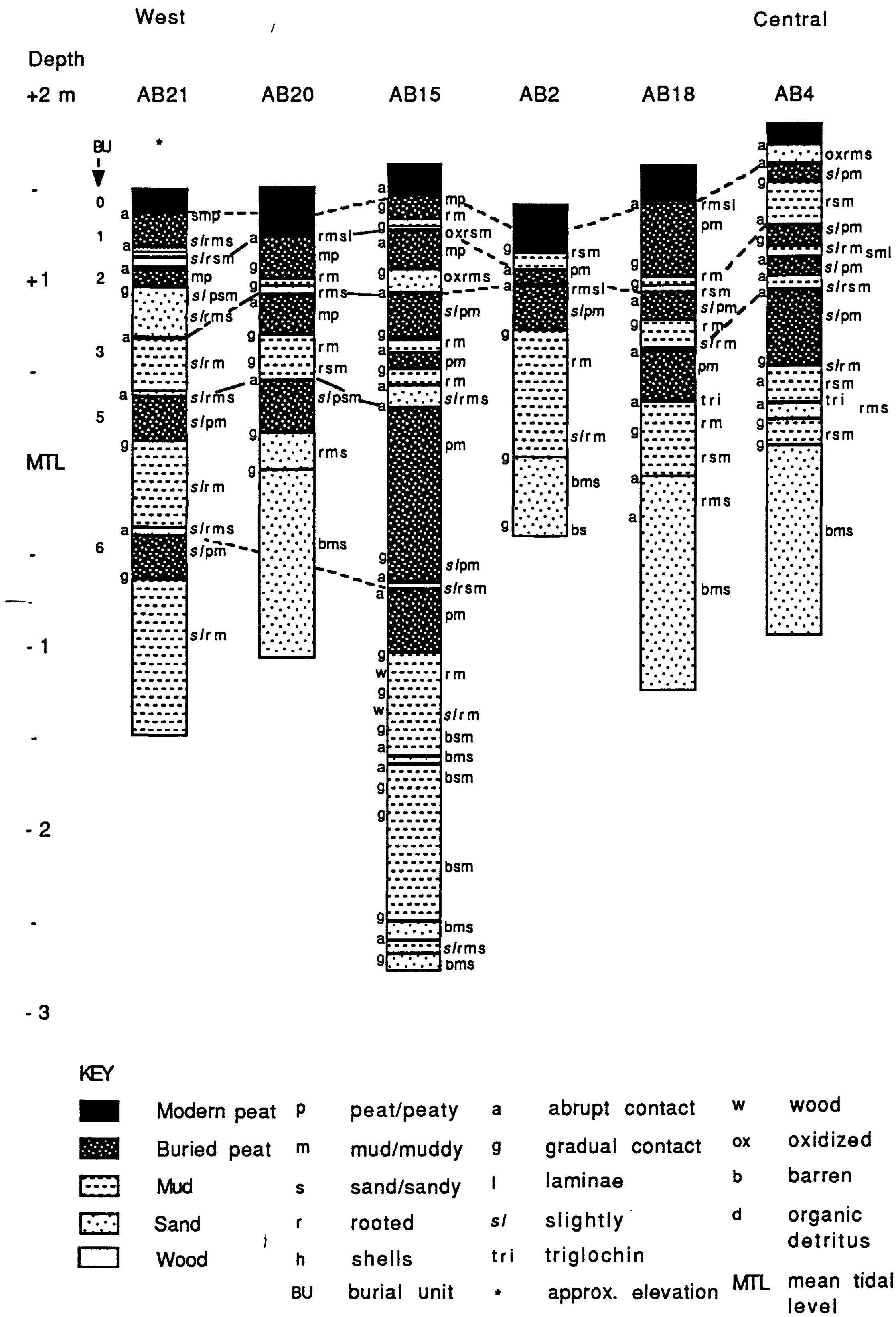

West
Central
Depth
+2 m
AB21
AB20
AB15
AB2
AB18
AB4
BU
+1
MTL
- 1
- 2
- 3
KEY
Modern peat
Buried peat
Mud
Sand
Wood
p peat/peaty
m mud/muddy
s sand/sandy
r rooted
h shells
BU burial unit
a abrupt contact
g gradual contact
l laminae
sl slightly
tri triglochin
* approx. elevation
w wood
ox oxidized
b barren
d organic detritus
MTL mean tidal level

Fig. 16A

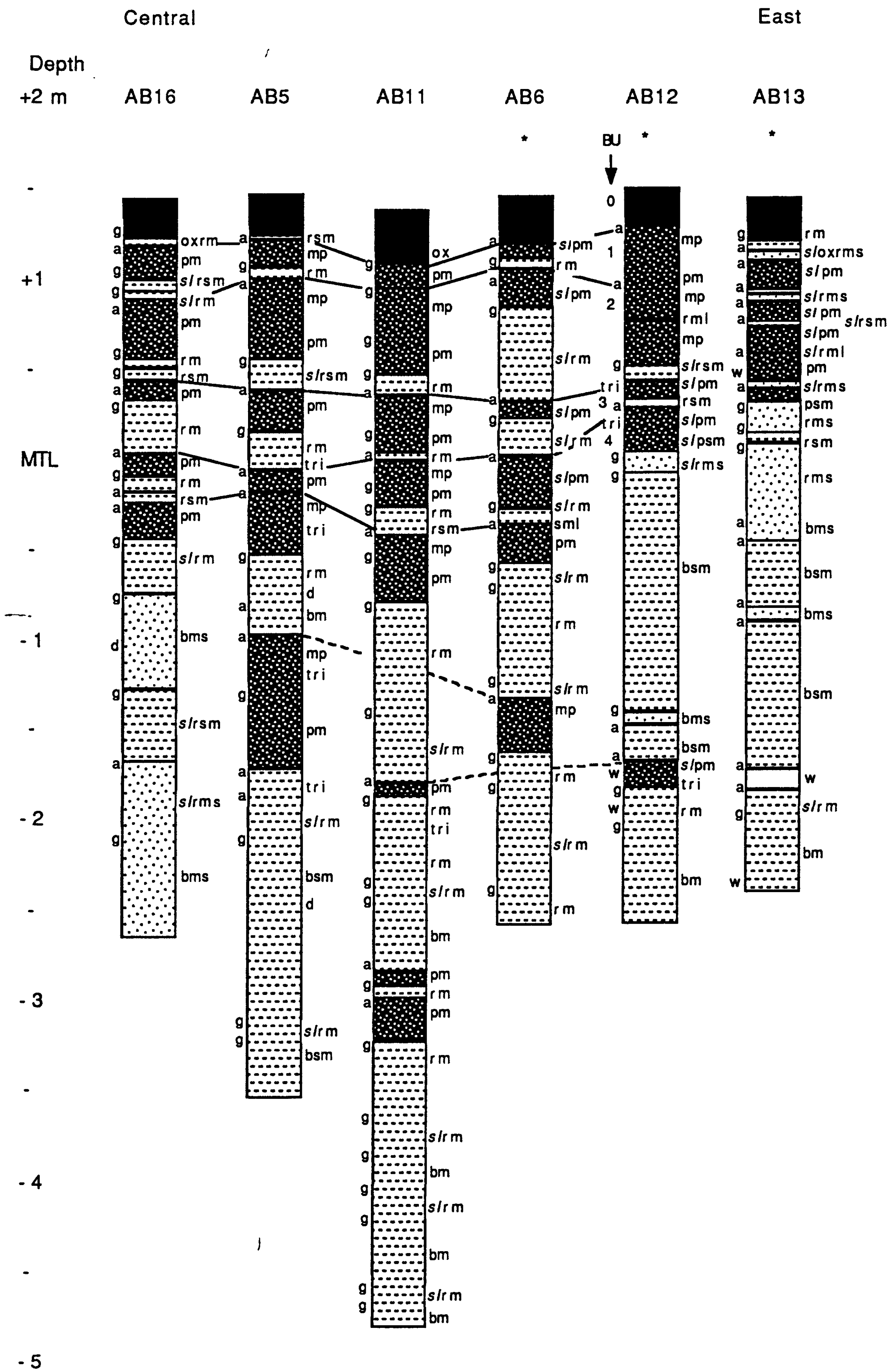

Central
East
Depth
+2 m
AB16
AB5
AB11
AB6
AB12
AB13
BU
0
1
2
3
4
+1
MTL
- 1
- 2
- 3
- 4
- 5
AB16: oxrm pm s/rsm s/rm pm rm rsm pm rm pm rm rsm pm s/rm bms s/rsm s/rms bms
AB5: rsm mp rm mp pm s/rsm pm rm tri pm mp tri rm d bm mp tri pm tri s/rm bsm d s/rm bsm
AB11: ox pm mp pm rm mp pm rm mp pm rm rsm mp pm rm s/rm pm rm tri rm s/rm bm pm rm pm rm s/rm bm s/rm bm s/rm bm
AB6: s/pm rm s/pm s/rm s/pm s/rm s/pm s/rm sml pm s/rm rm s/rm mp rm s/rm rm
AB12: mp pm mp rml mp s/rsm s/pm rsm s/pm s/psm s/rms bsm bms bsm s/pm tri rm bm
AB13: rm s/oxrms s/pm s/rms s/pm s/rsm s/pm s/rml pm s/rms psm rms rsm rms bms bsm bms bsm w s/rm bm

Fig. 16B

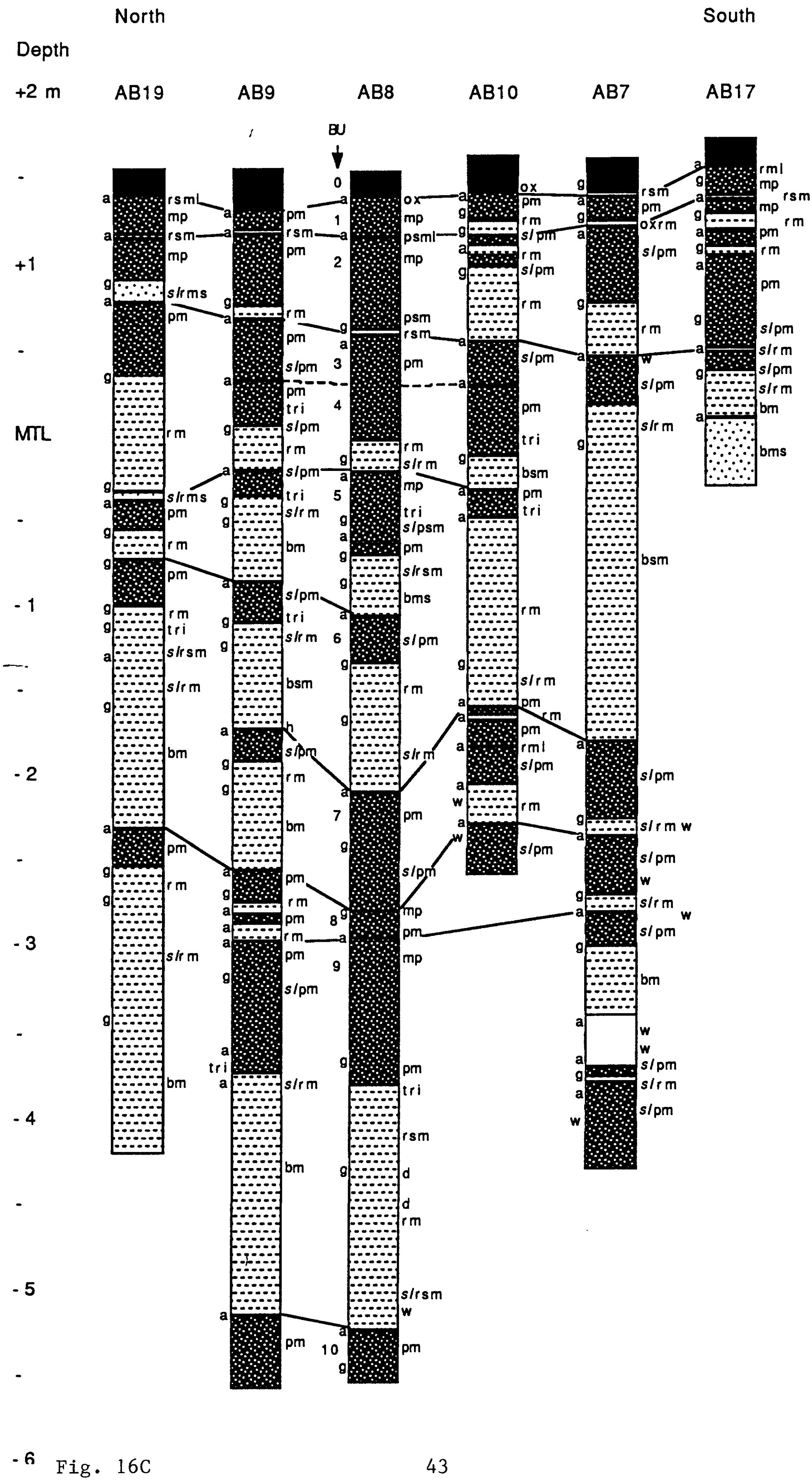

North
South
Depth
+2 m
AB19
AB9
AB8
AB10
AB7
AB17
BU
+1
MTL
- 1
- 2
- 3
- 4
- 5
- 6

Fig. 16C

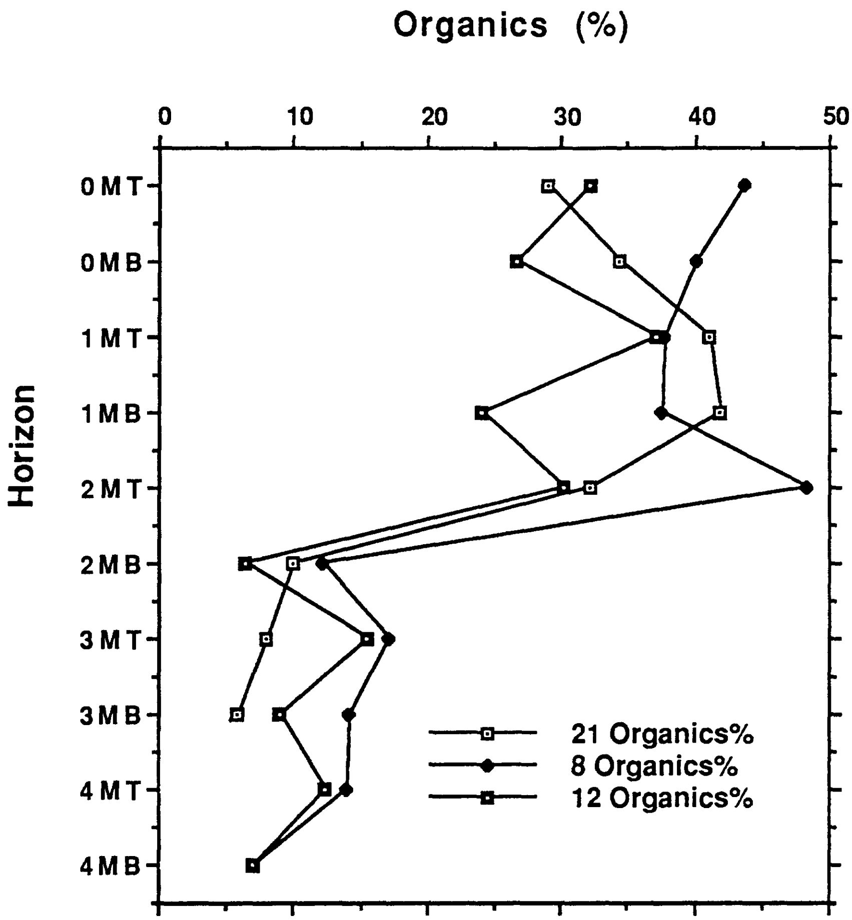
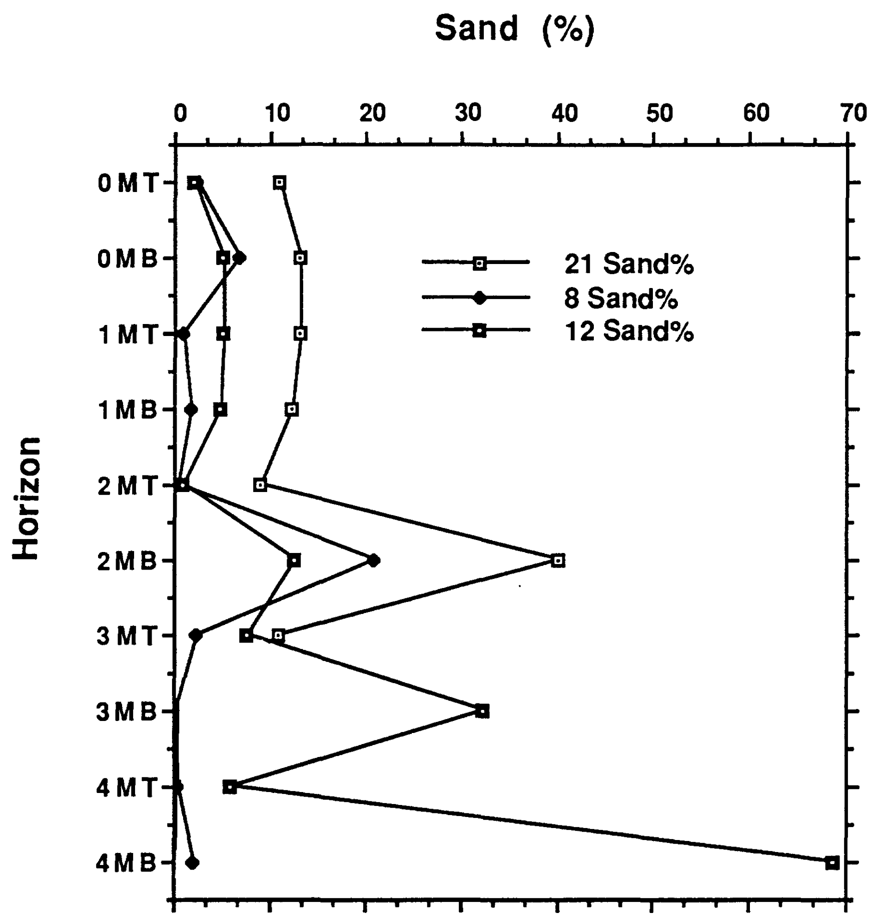
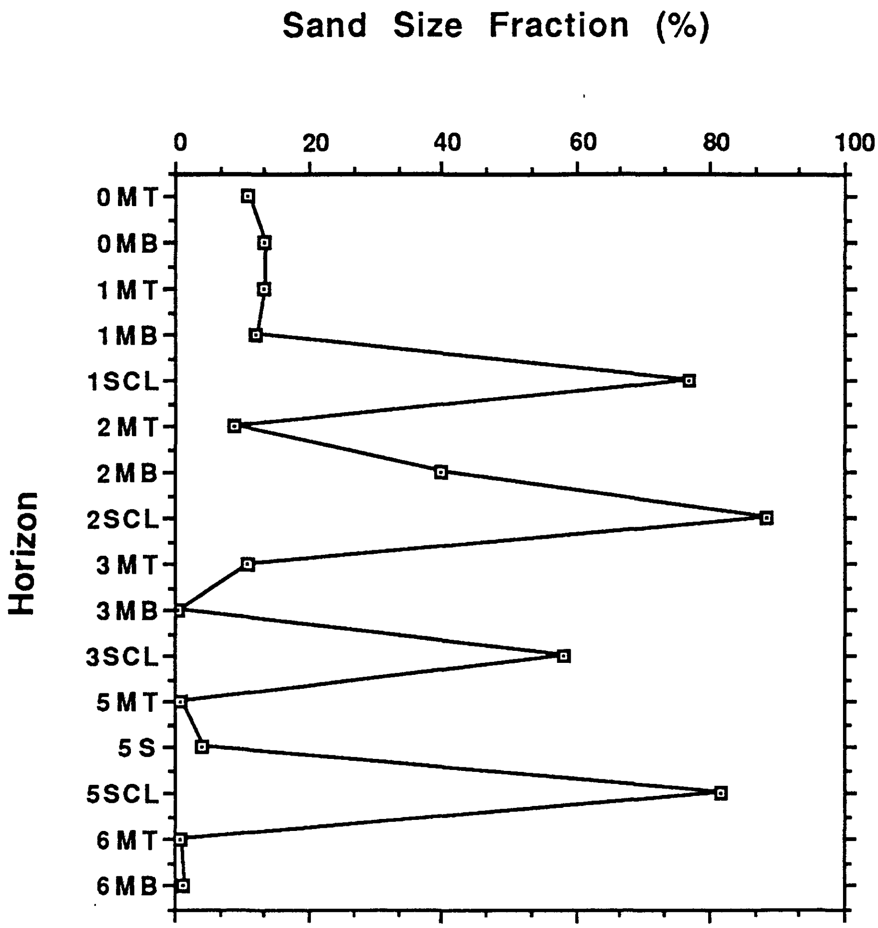

Organics (%)
0
10
20
30
40
50
0 M T
0 M B
1 M T
1 M B
2 M T
2 M B
3 M T
3 M B
4 M T
4 M B
Horizon
21 Organics%
8 Organics%
12 Organics%

Fig. 17



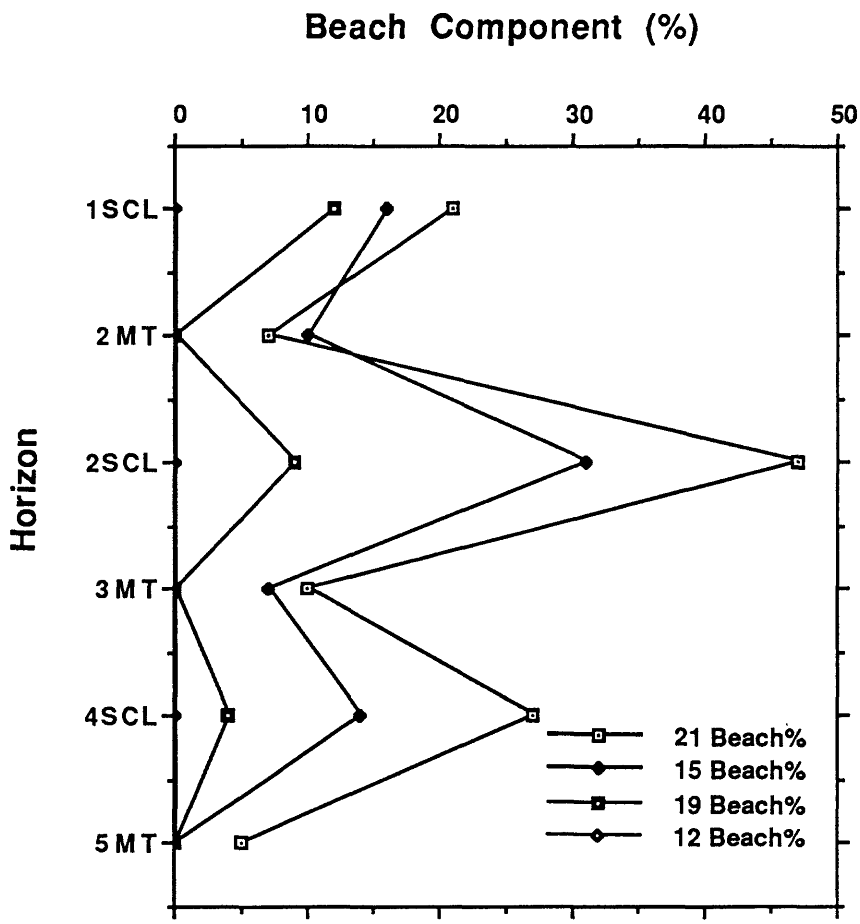
Sand (%)
0
10
20
30
40
50
60
70
Horizon
0 M T
0 M B
1 M T
1 M B
2 M T
2 M B
3 M T
3 M B
4 M T
4 M B
21 Sand%
8 Sand%
12 Sand%

Fig. 18



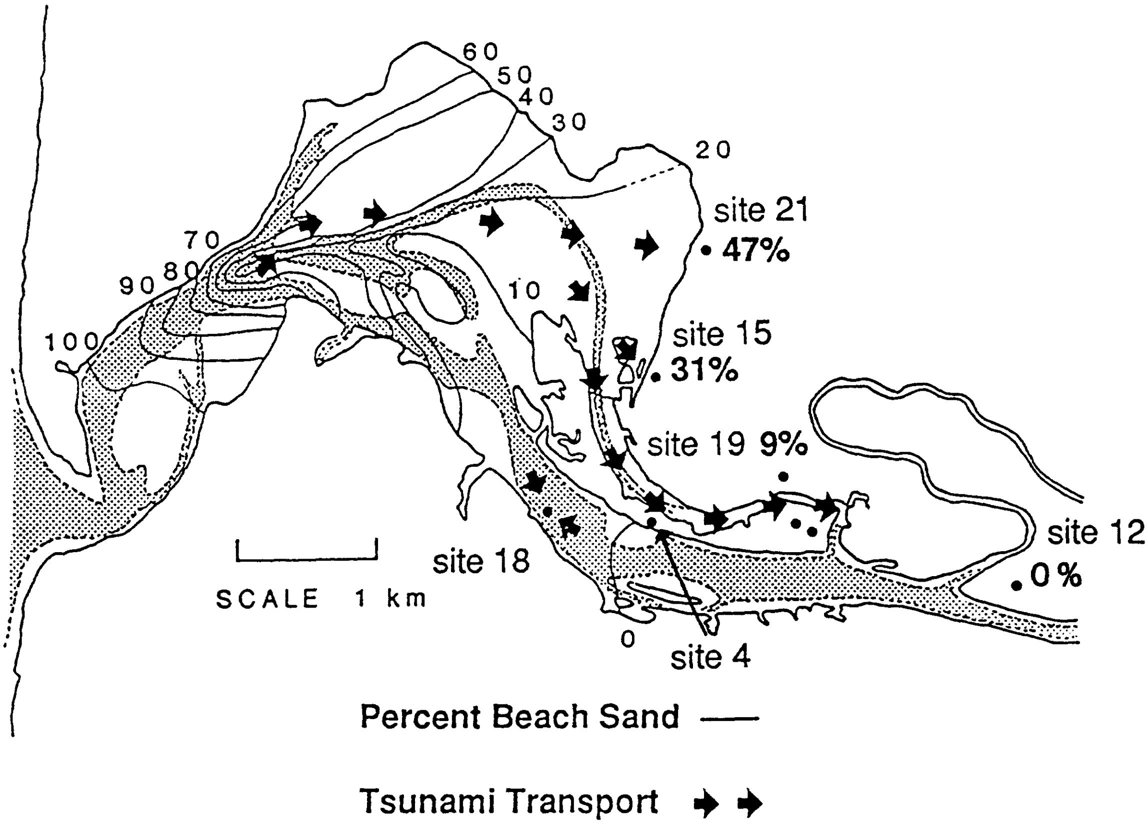
Sand Size Fraction (%)
0
20
40
60
80
100
Horizon
0MT
0MB
1MT
1MB
1SCL
2MT
2MB
2SCL
3MT
3MB
3SCL
5MT
5S
5SCL
6MT
6MB

Fig. 19



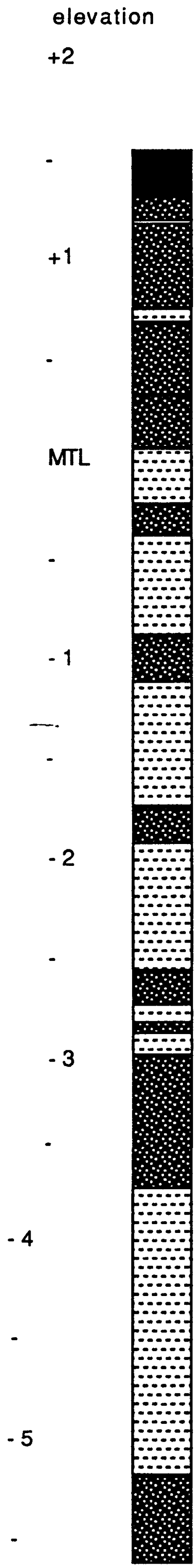
Beach Component (%)
0
10
20
30
40
50
1SCL
2MT
2SCL
3MT
4SCL
5MT
Horizon
21 Beach%
15 Beach%
19 Beach%
12 Beach%

Fig. 20



60
50
40
30
20
70
80
90
100
10
0
site 21
47%
site 15
31%
site 19 9%
site 12
0 %
site 18
site 4
SCALE 1 km
Percent Beach Sand
Tsunami Transport

Fig. 21



elevation	beta #	age (RCYBP)	age (C13 adj)	age (cal. BP)	location
+1.27	27182	160±50	120±50	0-290	MT1
+1.14	39181	480±60	500±60	474-645	MT2
+0.64	27184	800±80	760±80	561-903	MT3
+0.25		not dated			MT4
-0.18	26791	1490±80	1450±80	1260-1530	MT5
-0.87	27185	2210±80	2200±80	1999-2349	MT6
-1.68	26792	2620±60	2570±60	2479-2783	MT7
-2.57	27186	2890±70	2830±70	2779-3205	MT8
-3.05	38861	3140±50	3070±50	3168-3389	MT9
-5.12	26790	4510±80	4480±80	4869-5319	MT10

MT=marsh top

-6 Fig. 22

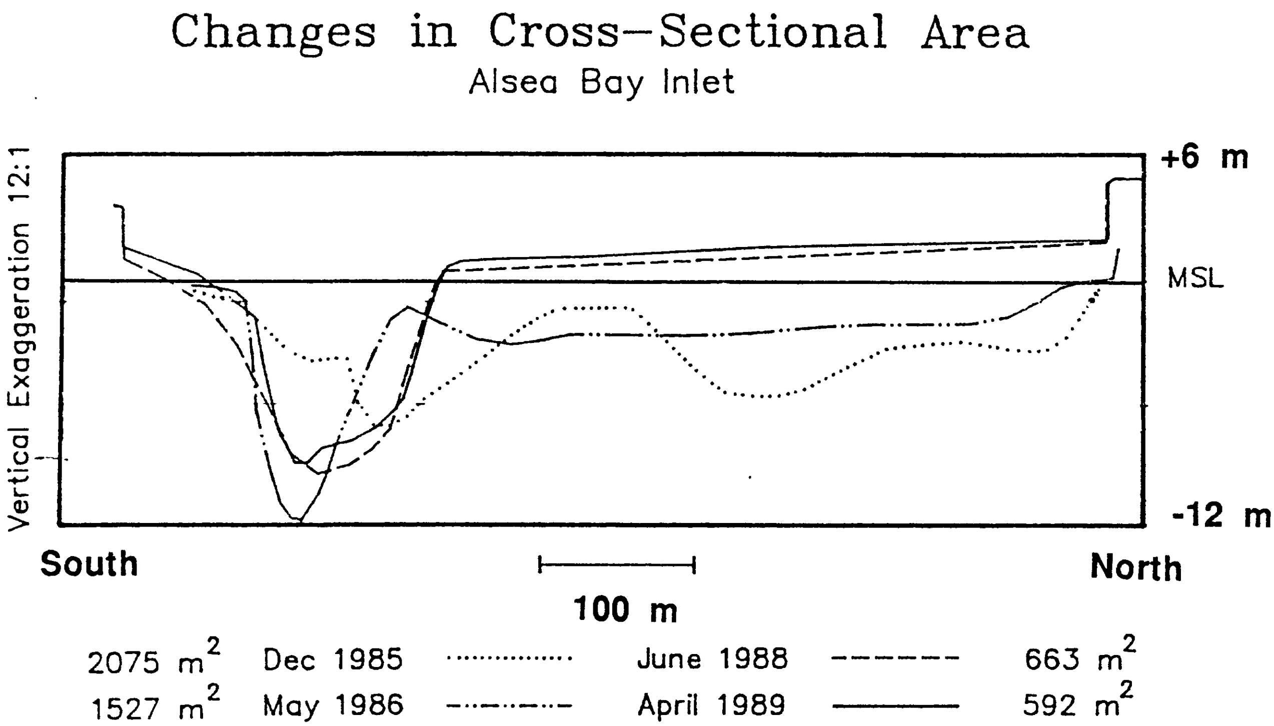
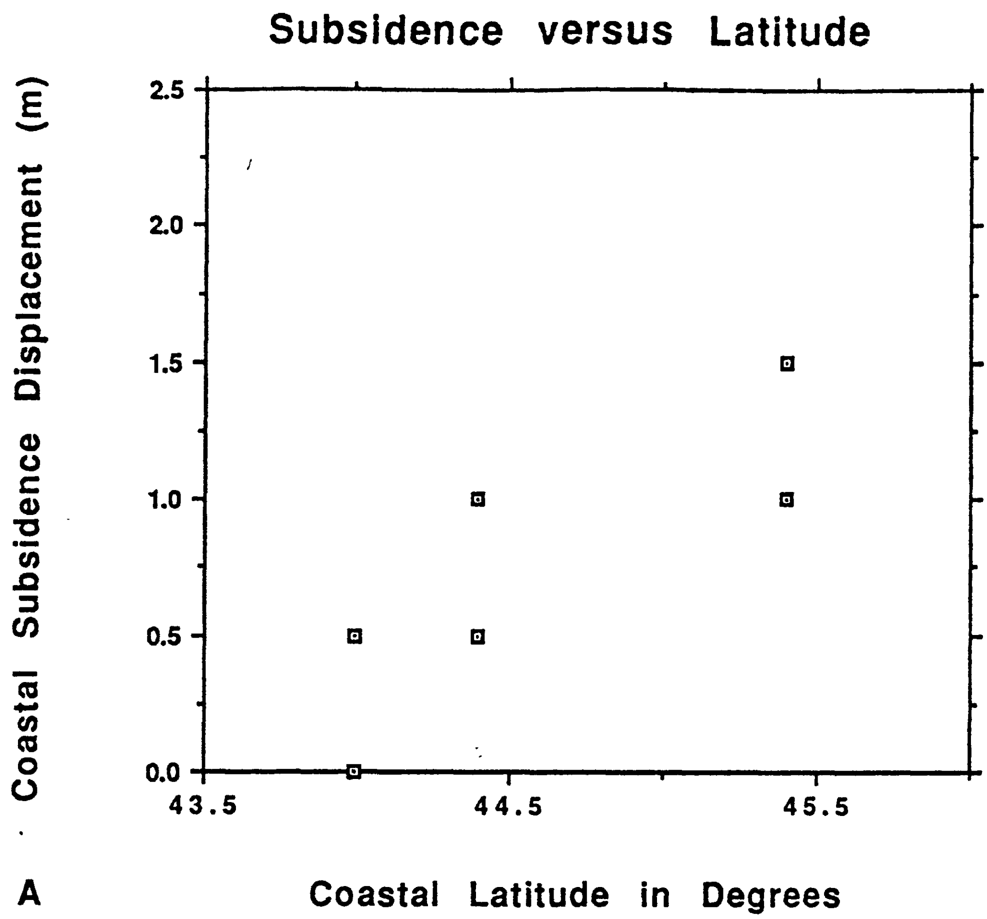
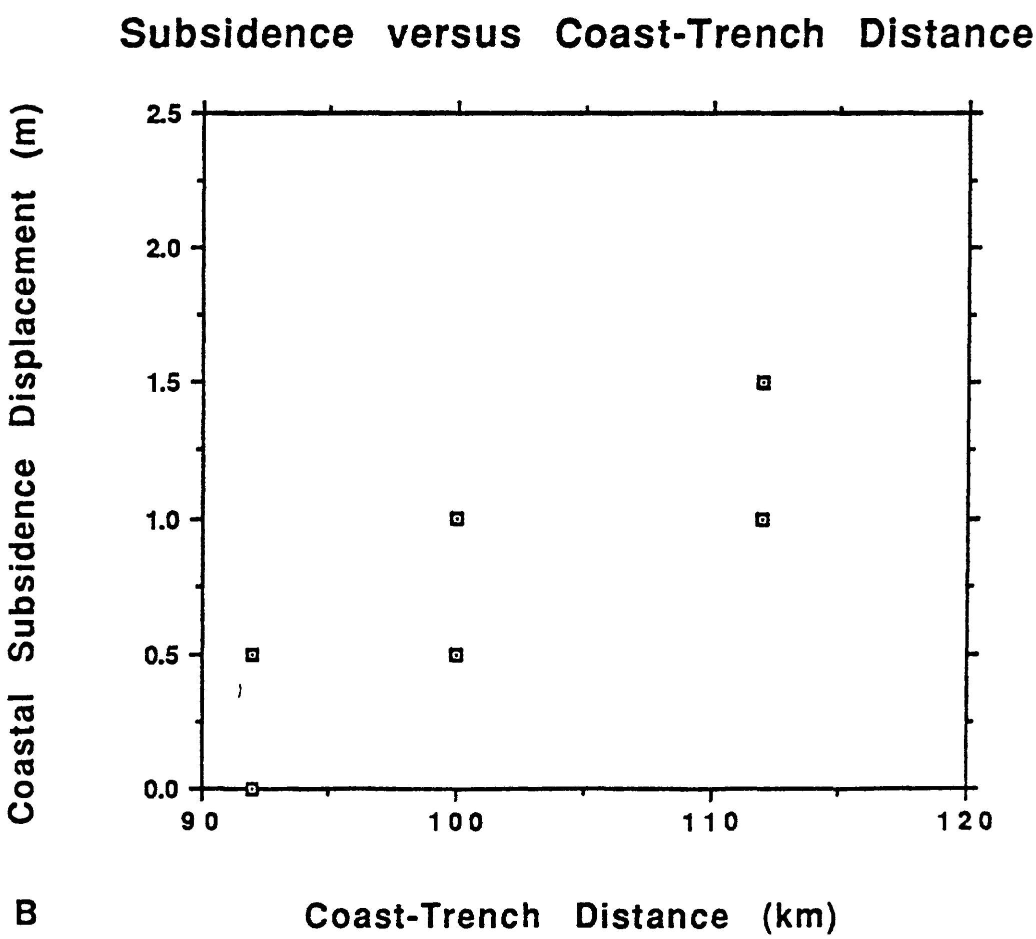

Changes in Cross-Sectional Area
Alsea Bay Inlet
Vertical Exaggeration 12:1
+6 m
MSL
-12 m
South
North
100 m
2075 m2 Dec 1985
1527 m2 May 1986
June 1988 663 m2
April 1989 592 m2

Fig. 23


Subsidence versus Latitude
Coastal Subsidence Displacement (m)
2.5
2.0
1.5
1.0
0.5
0.0
43.5
44.5
45.5
Coastal Latitude in Degrees

A


Subsidence versus Coast-Trench Distance
Coastal Subsidence Displacement (m)
2.5
2.0
1.5
1.0
0.5
0.0
90
100
110
120
Coast-Trench Distance (km)

B

Fig. 24

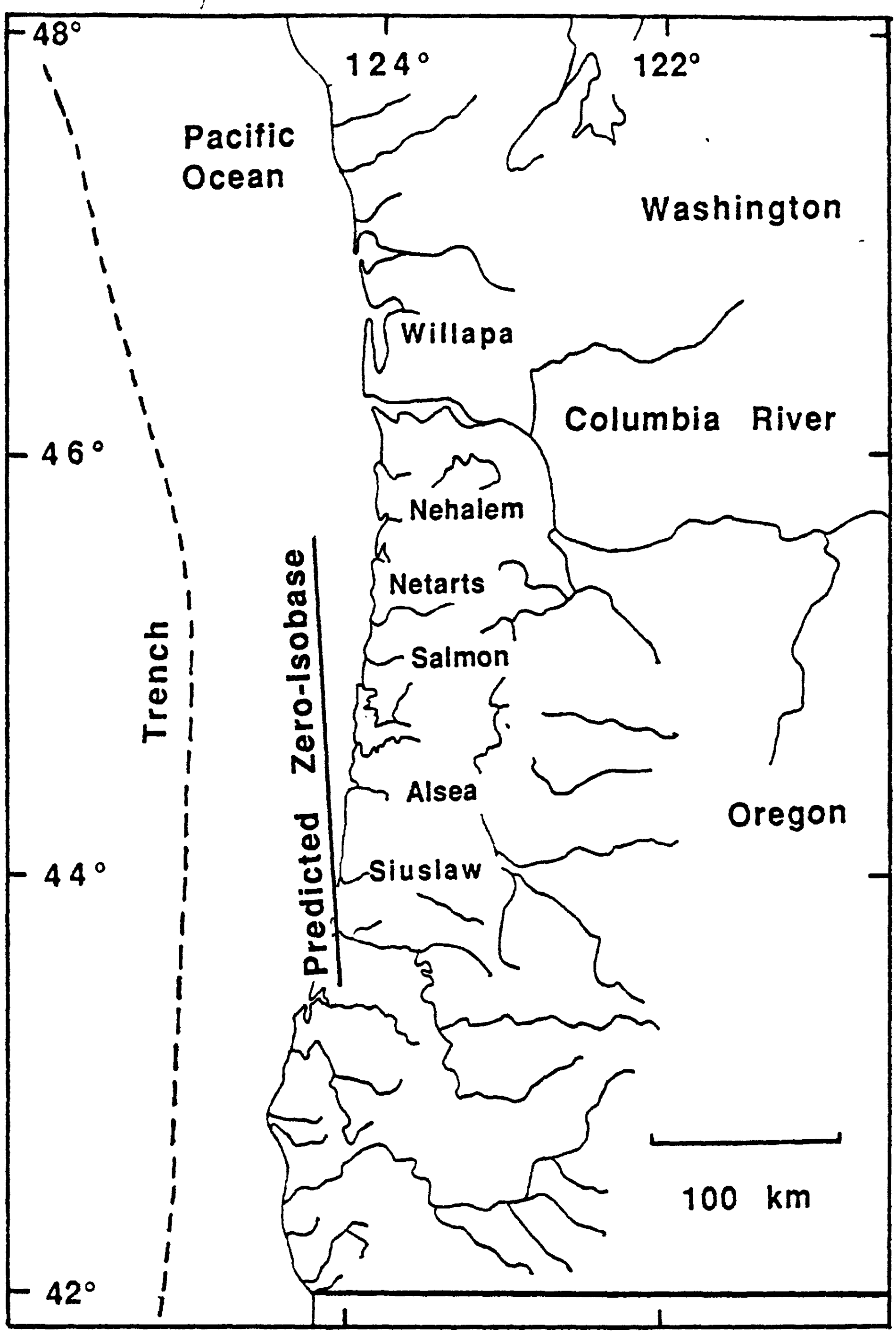
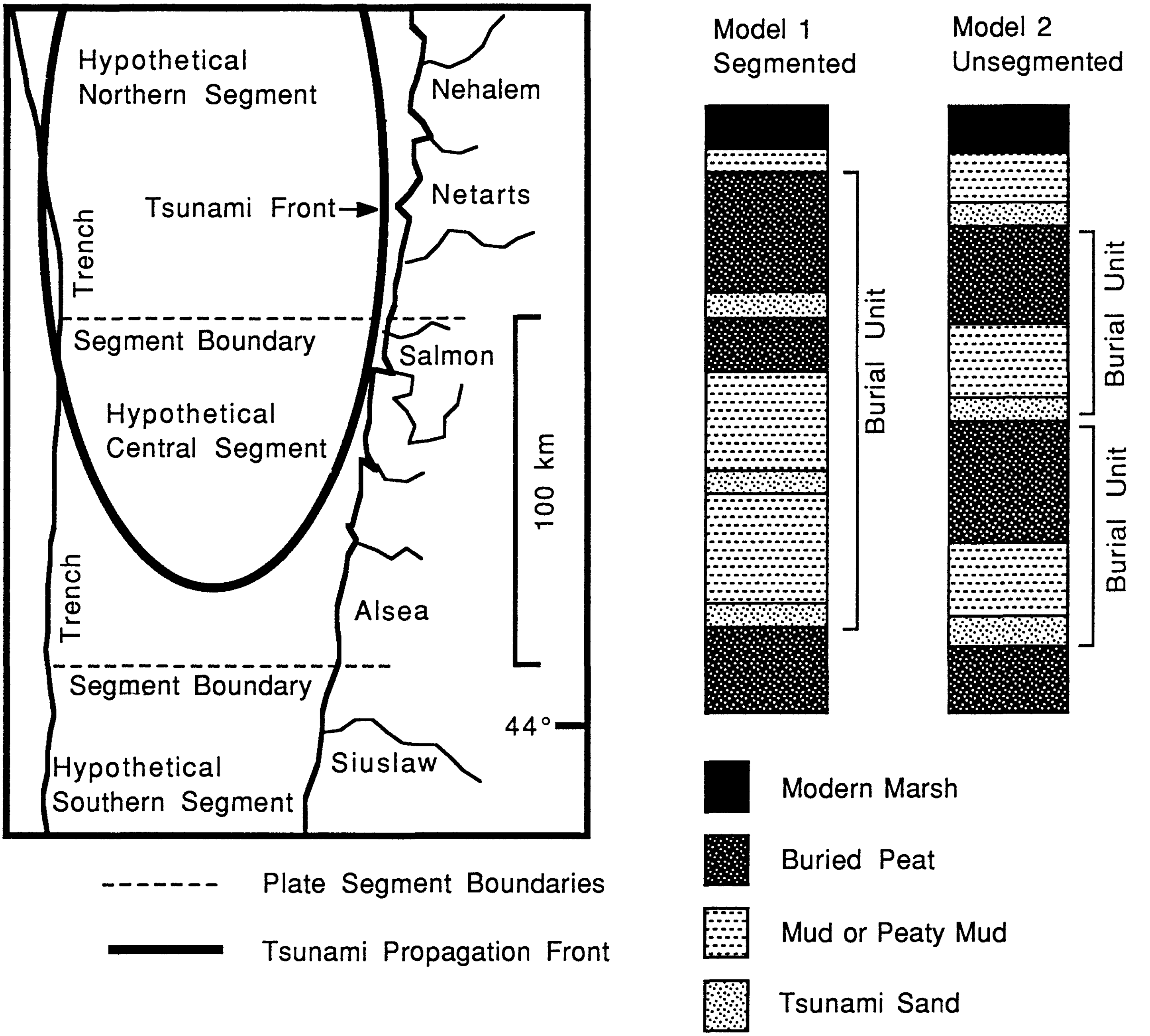

48°
124°
122°
Pacific
Ocean
Washington
Willapa
Columbia River
46°
Nehalem
Netarts
Salmon
Trench
Predicted Zero-Isobase
Alsea
Oregon
44°
Siuslaw
100 km
42°

Fig. 25



Hypothetical
Northern Segment
Nehalem
Tsunami Front
Netarts
Trench
Segment Boundary
Salmon
Hypothetical
Central Segment
100 km
Trench
Alsea
Segment Boundary
44°
Hypothetical
Southern Segment
Siuslaw
Plate Segment Boundaries
Tsunami Propagation Front
Model 1
Segmented
Model 2
Unsegmented
Burial Unit
Burial Unit
Burial Unit
Modern Marsh
Buried Peat
Mud or Peaty Mud
Tsunami Sand

Fig. 26