Coastal Evidence For Great Earthquakes In Western Washington

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The Pacific Northwest has a history of great earthquakes—shocks of magnitude 8 or larger—and of tsunamis generated by them. The most recent of these earthquakes, however, predates the Lewis and Clark expedition by about a century. Only since 1980 have scientists discovered that great earthquakes repeatedly struck British Columbia, Washington, Oregon, and California in the past few thousand years.

This booklet illustrates some of the geologic clues that led to this discovery.

GLOSSARY

Intertidal zone. The area between low tide and high tide. It has a vertical range of about 10 feet at Willapa Bay and Grays Harbor, Washington. Tideflats are common in the lower part of the intertidal zone, while tidal marshes and tidal swamps are common in the upper part of the intertidal zone (fig. 16*A*).

Magnitude. A number used to represent the size of an earthquake. Magnitude is not necessarily related to intensity—how strong an earthquake feels at a given place—but it is related to the total amount of energy released. A whole-number difference in magnitude (for example,the difference between magnitude 7 and magnitude 8) corresponds to a 32-fold difference in the amount of energy released. The minimum magnitude for an earthquake to be termed "great" is magnitude 8, about the size of the 1906 San Francisco earthquake. The largest recorded earthquake—1960 Chile (fig. 10*B*)—had a magnitude of 9.5.

Soil. In this report the term is used much as a farmer would, to refer to surficial material in which plants are rooted.

Subduction. The descent of one **tectonic plate** beneath another. At the Cascadia subduction zone, the Juan de Fuca plate descends eastward beneath the North America plate, along a fault that runs from southern British Columbia to northern California. This plate-boundary fault intersects the seafloor far offshore (fig. 12*A*, barbed line) but extends eastward beneath the Pacific coast, into a currently bulging region cartooned in figure 9.

Submergence. The inundation of land. Along a coast, it may result from lowering of land (subsidence) or from rise of the sea.

Tectonic plate. A slab tens of miles thick that includes the Earth's crust and which moves relative to other such plates. Most earthquakes occur where plates rub against one another.

Tsunami. An impulsively generated wave, or train of waves. Many tsunamis are caused by abrupt raising or lowering of the seafloor during earthquakes.

CONVERSIONS

Multiply	*By*	*To obtain*
1 kilometer (km)	0.6	miles
1 meter (m)	3.3	feet
1 centimeter (cm)	2.5	inches

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Past great earthquakes at the Cascadia subduction zone lowered coastal land into tidal water, killing thousands of trees. Stumps of some of the spruce trees killed about A.D. 1700 can be seen at low tide along the west shore of Willapa Bay, where they have been exhumed by waves and partly covered with seaweed. Stripes on handle at left are 10 cm long.

CONTENTS

ILLUSTRATIONS

COASTAL EVIDENCE FOR GREAT EARTHQUAKES IN WESTERN WASHINGTON

By Brian F. Atwater

SUMMARY

Buried marsh and forest soils in southern coastal Washington show that earthquakes of magnitude 8 or larger (great earthquakes) probably occur at the Cascadia subduction zone. Similar soils in Alaska and Chile record lowering of coastal land that accompanied great subduction-zone earthquakes in those regions. Fossil plants show that many of the soils in Washington stood above most or all high tides until the onset of burial, when the soils were frequently submerged by tidal water at least ½ m deep. In some cases, fossil plants further show that this submergence resulted from abrupt lowering of the land, not from gradual rise of the sea. Some of the buried soils are mantled with sand that was probably deposited by tsunamis. Sequences of buried soils give evidence that hundreds of years commonly elapse between great earthquakes in southern coastal Washington.

INTRODUCTION

Great subduction earthquakes pose a hazard to the northwestern United States and adjacent Canada. This hazard went undetected until the 1980's, when earth scientists began to assemble what soon became overwhelming evidence that the Cascadia subduction zone has produced great earthquakes in the past and is capable of doing so again (Hyndman, 1995).

The most decisive of this evidence came from coastal geology. Great earthquakes on subduction zones can leave lasting marks in coastal geology by making coastal land subside, by generating tsunamis, and by causing sand to liquefy. By 1995, evidence for subsidence, tsunamis, and (or) shaking had been found at more than a dozen bays and river mouths along the Pacific coast from northern California to southern British Columbia (Atwater and others, 1995).

This report illustrates coastal evidence for past great earthquakes in southwestern Washington. The examples, prefaced with modern analogs from Alaska and Chile, show simple ways that abrupt subsidence and accompanying tsunamis can be detected centuries after they occurred. This report does not illustrate evidence that shaking accompanied the subsidence and tsunamis at the Cascadia subduction zone. Such evidence, first recognized by Stephen F. Obermeier, mainly takes the form of sand-filled cracks (Atwater, 1994; Obermeier, 1995).

The report is excerpted from volume 1 of "Assessing earthquake hazards and reducing risk in the Pacific Northwest", U.S. Geological Survey Professional Paper 1560. This volume, published in 1996, was edited by Albert M. Rogers, Timothy J. Walsh, William J. Kockelman, and George R. Priest. The chapter excerpted here was mostly written in 1990.

H. Edward Clifton, David K. Yamaguchi, Alan R. Nelson, Timothy J. Walsh, Barbara C. Hillier, John Synnefakis, and Jeffrey A. Troll provided comments that improved the chapter. Susan E. Mayfield designed the cover. Mary Ann Reinhart contributed most of the measurements shown in figure 22*C*.

GREAT EARTHQUAKES AT SUBDUCTION ZONES CAN CAUSE SUDDEN COASTAL SUBMERGENCE . . .

Regional lowering of the land commonly accompanies great earthquakes at subduction zones. This subsidence can be viewed as part of a cycle of deformation in the continental plate (fig. 9). Before an earthquake, the continental plate bulges over and behind a stuck patch on the plate boundary. During the earthquake, the bulge collapses and the leading edge of the continental plate stretches and thins from lurching seaward while most of the remainder of the plate stands still. Such elastic thinning can produce a belt of subsidence, as illustrated by great subduction-zone earthquakes in Alaska and Chile (fig. 10).

The subsidence in Alaska and Chile dropped well-vegetated lowlands into the intertidal zone. This submergence led to the widespread deposition of tideflat mud on such lowlands as an Alaskan spruce forest (fig. 11*A*) and a Chilean pasture (fig. 11*B*). The change from well-vegetated lowland to tideflat began immediately after each earthquake. First-year casualties in Alaska included Sitka spruce (Plafker, 1969, figs. 12, 19, 22). Tidal-marsh plants later colonized the post-earthquake tideflats (fig. 11).

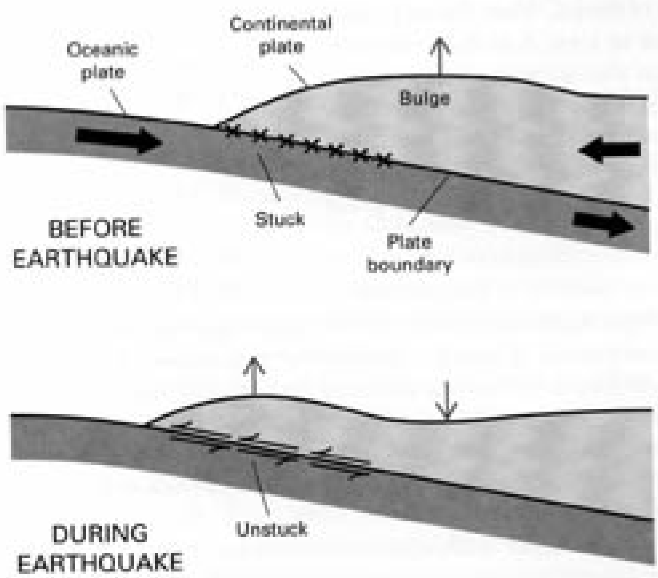


Figure 9. Deformation of a continental plate before and during a subduction-zone earthquake. Black arrows show directions of stress within the plates; colored arrows show exaggerated vertical displacement of the land surface; barbs indicate direction of plate movement. From models of Plafker (1972, p. 913) and Thatcher and Rundle (1984).

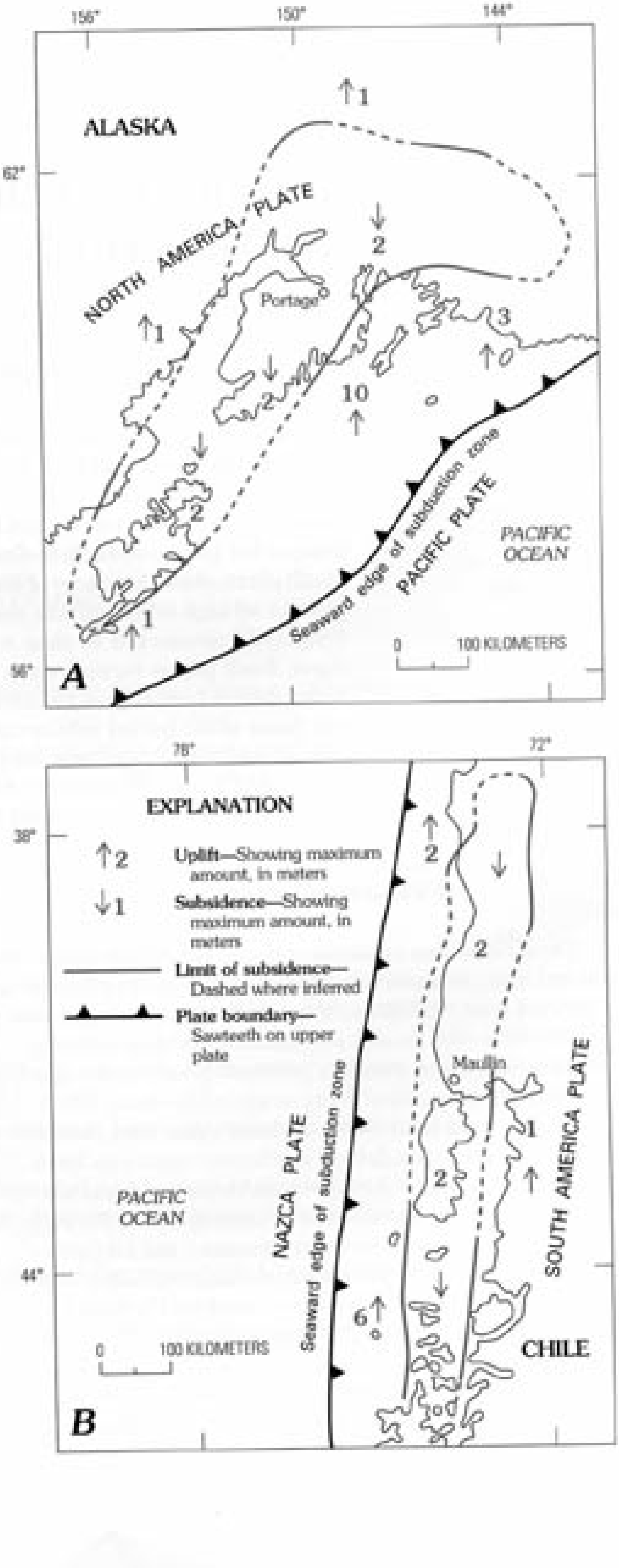


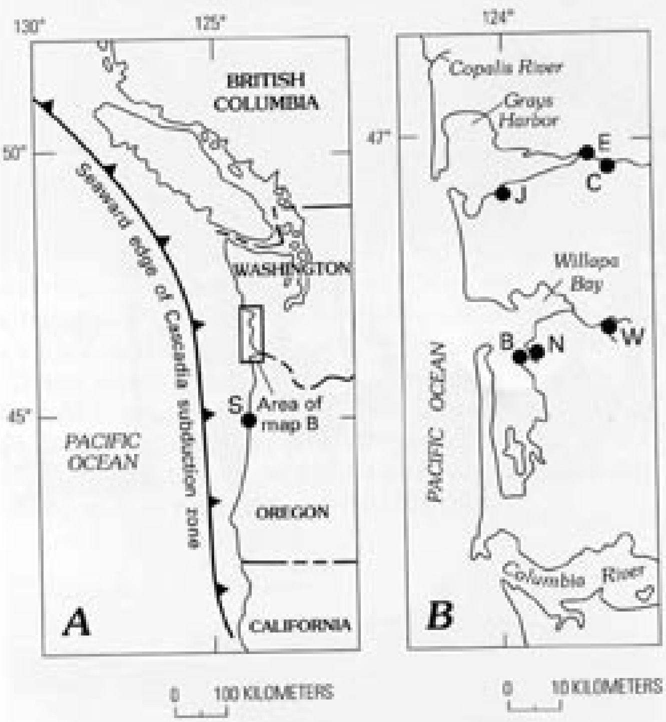
Figure 10 (facing column). Land-level change accompanying two great subduction-zone earthquakes. *A*, Alaska, 1964, magnitude 9.2 (Plafker, 1969). *B*, Chile, 1960, magnitude 9.5 (Plafker and Savage, 1970). Magnitudes are from Kanamori (1977).

...AND THE CONSEQUENT BURIAL OF COASTAL LOWLANDS

Figure 11. Geologic records of coastal land subsidence from great earthquakes in Alaska and Chile. Tidal-marsh plants (**p**) locally colonize mud (**m**) of post-earthquake tideflats. *A*, dead Sitka spruce forest near Portage, Alaska (fig. 10*A*). Mud 1–2 m thick accumulated on the forest floor between 1964, when the forest became tideflat, and 1973, when the picture was taken (Ovenshine and others, 1976). Photograph by A.T. Ovenshine. *B*, former pasture near Maullín, Chile (fig. 10*B*), mostly covered by mud since subsiding in 1960. Still-exposed soil (**s**) of pre-earthquake pasture undergoes erosion along meandering tidal channel (**c**). Photograph taken at low tide in 1988.

BURIED LOWLANDS ARE COMMON AND CONSPICUOUS IN SOUTHERN COASTAL WASHINGTON

Buried lowlands border all four estuaries of southern coastal Washington—the lower Copalis River, Grays Harbor, Willapa Bay, and the lower Columbia River (fig. 12). The large dots in figure 12*B* locate examples shown in this chapter.



Many of the buried lowlands retain recognizable lowland features. The soil of the former marsh in figure 13 has lateral extent comparable to that of the modern marsh. Rooted in the buried-marsh soil are fossil stems and leaves of the grass *Deschampsia caespitosa*, which is also the dominant plant of the modern marsh (see detailed photographs in fig. 19).

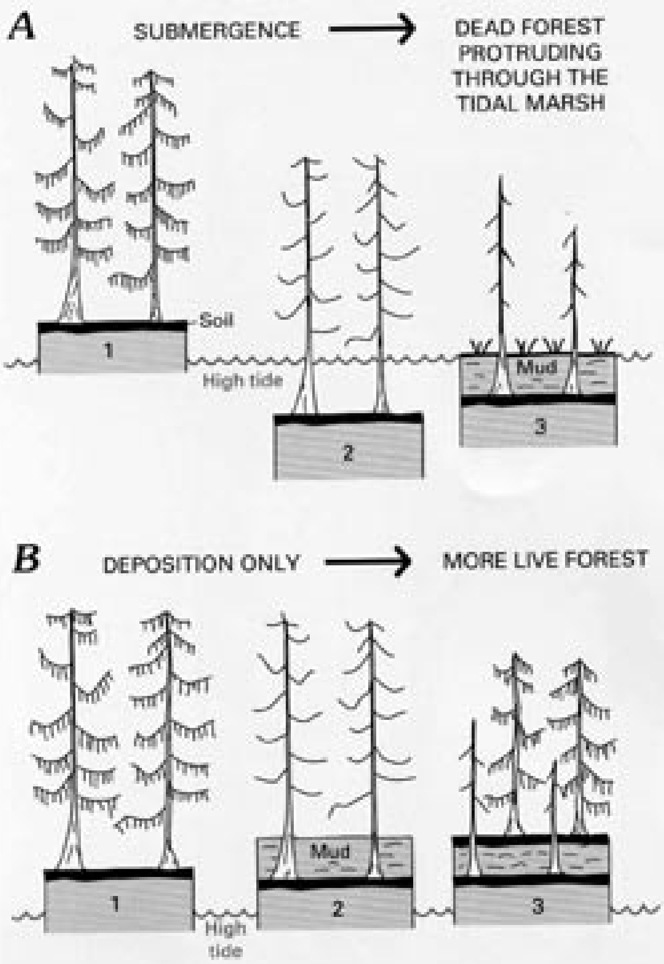
The most conspicuous buried lowlands are marked by standing dead trunks of western redcedar (fig. 14). Such snags impressed a naturalist on a nineteenth-century railroad survey: "On some of the tide-meadows about Shoalwater [Willapa] bay dead trees of this species only are standing, sometimes in groves * * *" (Cooper, 1860, p. 26). The redcedar snags, mostly rooted below present high tide, are scattered along nearly 100 km of coast from the Copalis River to the Columbia River. The trees died about A.D. 1700 (Yamaguchi and others, 1989; Atwater and others, 1991).

Figure 12 (facing column). The Cascadia subduction zone and southern coastal Washington. *A*, Cascadia subduction zone. Sawteeth are on overriding North America plate. **S** is the Salmon River estuary. *B*, southern coastal Washington. **B** is Bay Center; **C**, Chehalis River and Blue Slough; **E**, Elliott Slough; **J**, Johns River; **N**, Niawiakum River; and **W**, Willapa River.

Figure 13. Soil of a former marsh (**m**), buried and later exhumed along the Johns River, Grays Harbor (fig. 12 *B*). Especially resistant to erosion, the soil supports the bench on which the people (**p**) are standing. The water is at low tide; the highest modern tides inundate the live marsh behind the people. Locality 13 of Atwater (1992).

Figure 14. Dead forest of western redcedar (*Thuja plicata*) protruding through a brackish-water tidal marsh along the Copalis River (Atwater, 1992, figs. 2, 5). The floor of the dead forest lies buried below the marsh surface. The live forest in the background occupies the upland above the highest tides.

BURIAL OF LOWLANDS IN COASTAL WASHINGTON RESULTED FROM SUBMERGENCE



Tidal submergence (fig. 15*A*) led to the demise of the redcedar forest shown in figure 14. Deposition alone—by storm, flood, or tsunami—would not have promoted such submergence (fig. 15*B*).

Buried spruce forests in coastal Washington give further evidence for submergence. Mud just above the soils of these forests commonly contains the below-ground stems (rhizomes) of *Triglochin maritima* or *Carex lyngbyei*, grass-like plants that in coastal Washington are rooted mainly ½ to 1 ½ m lower in elevation than the lowest Sitka spruce (figs. 16, 17). The spruce stumps and *T. maritima* rhizomes thus suggest that the land was lowered at least ½ to 1 ½ m relative to the sea. In comparison, the subsidence from great subduction-zone earthquakes in Alaska and Chile caused as much as 2 m of widespread coastal submergence (fig. 10).

Figure 15 (facing column). Burial of the floor of a coastal lowland forest. *A*, deposition triggered by tidal submergence. The result is a dead forest that protrudes through a tidal marsh, as in figures 11*A* and 14. *B*, deposition by storm, flood, or tsunami without lasting tidal submergence. The forest floor builds farther above high tides, contrary to the result shown in figures 11*A* and 14.

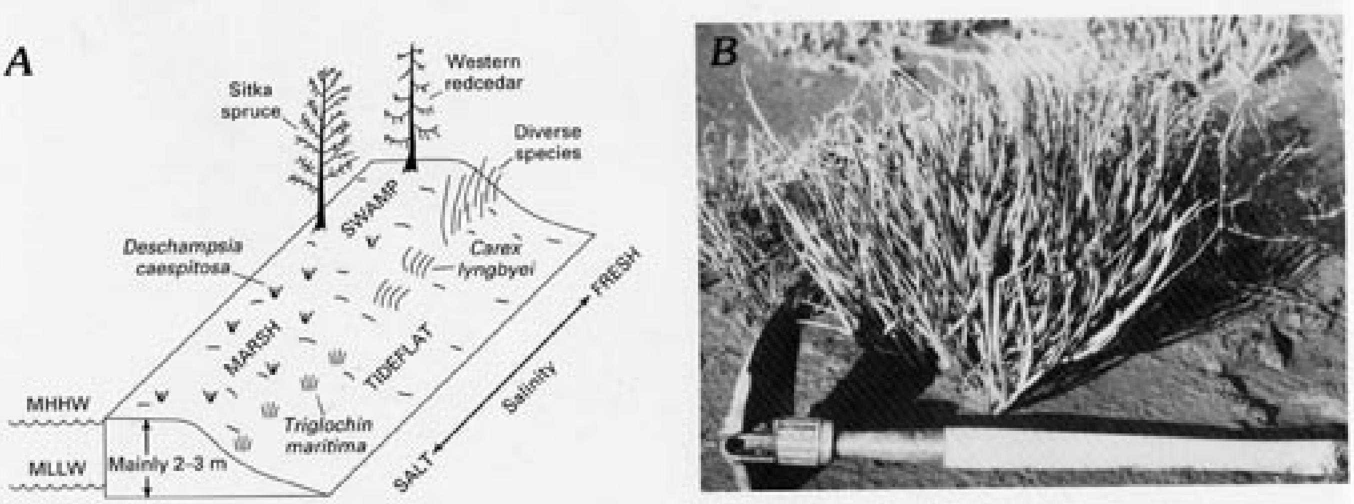


Figure 16. Dominant plants of coastal marshes and swamps in southern Washington. *A*, distribution of plants relative to tides and salinity. MHHW is mean higher high water; MLLW is mean lower low water. From descriptions by Franklin and Dyrness (1973, p. 294–295), Kunze and Cornelius (1982), and Weinmann and others (1984). *B*, *Triglochin maritima* on a muddy tideflat, Willapa Bay. The shovel handle is 0.5 m long.

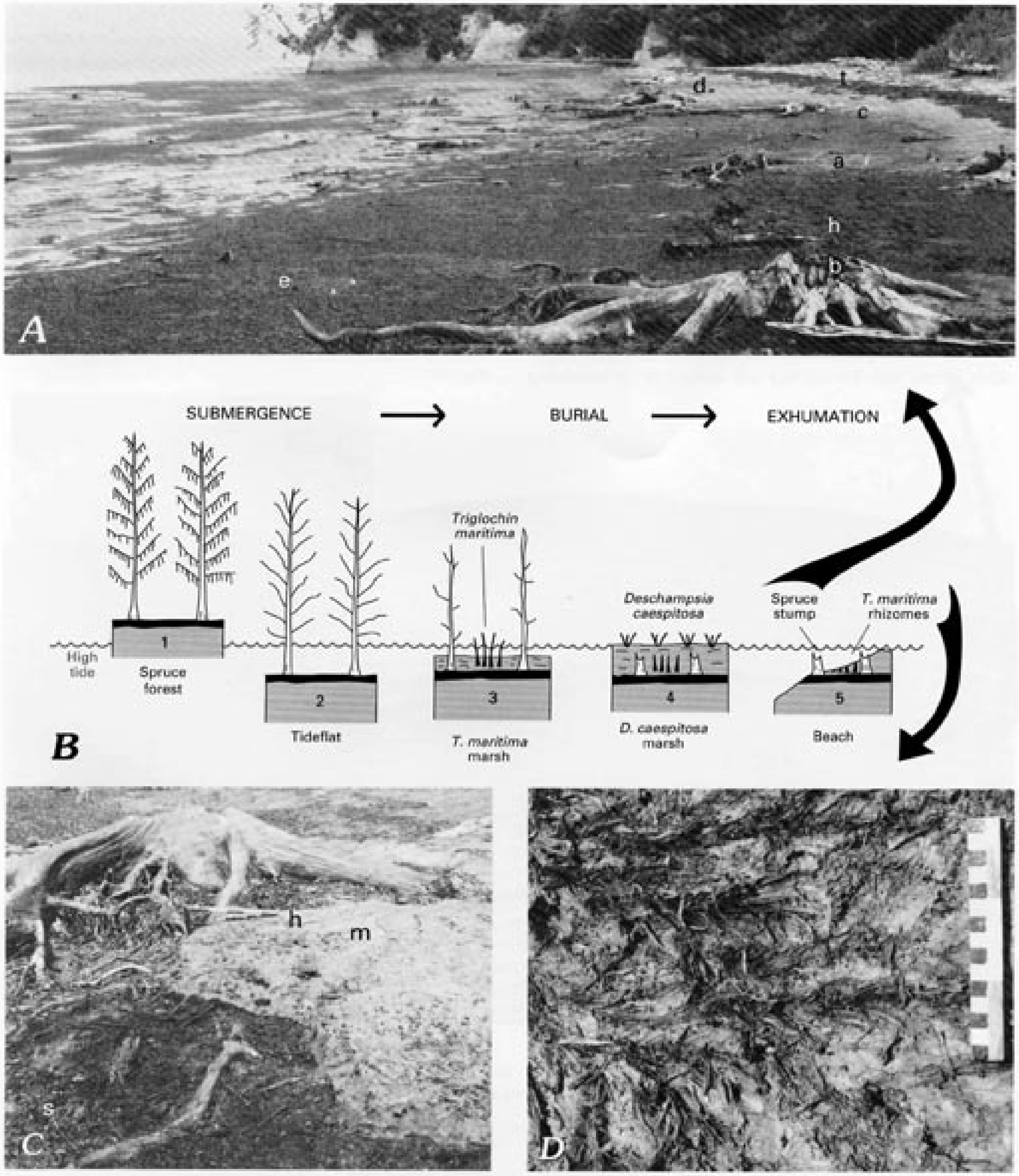


Figure 17. Formerly buried spruce stumps exhumed on a beach at Bay Center, Willapa Bay (fig. 12*B*). The shovel handle (**h**) in *A* and *C* is 0.5 m long. Locality 16 of Atwater (1992). *A*, overview, showing spruce stumps (**a–d**) at low tide on the beach. Leaves of eelgrass (**e**, *Zostera marina*), a salt-water aquatic plant, mantle much of the beach and mark the level of highest summertime tides (**t**). *B*, inferred sequence of events leading to burial and exhumation. *C*, detail of stump (**a**) showing peaty soil (**s**) in which the stump is rooted and lowermost 0.3 m of the tideflat mud (**m**) that accumulated on this soil. *D*, vertical view of *Triglochin maritima* rhizomes in mud at lower right in *C*. Individual rhizomes, which include attached leaf bases, are mostly perpendicular to 15-cm scale.

SUBMERGENCE OF BURIED LOWLANDS IN COASTAL WASHINGTON HAPPENED ABRUPTLY

Fossil plants and abrupt tops of buried lowland soils in southern coastal Washington show that submergence of the lowlands happened so quickly that it is better explained by abrupt lowering of the land than by gradual rise of the sea.

Some of the spruce stumps rooted in the youngest buried lowland soil show little or no thinning of outer annual growth rings (fig. 18). This lack of thinning suggests spruce death as sudden as that from earthquake-induced submergence in Alaska (fig. 11*A*). Thinning of outer rings would be expected of trees that suffered slow death from gradual submergence.

Herbaceous plants rooted in some buried lowland soils retain stems and leaves that are entombed in overlying tideflat mud. The most conspicuous of these fossils belong to *Deschampsia caespitosa*, the chief grass in high parts of salt- and brackish-water lowlands in coastal Washington (figs. 16*A*, 19*A–C*). Sudden submergence followed by rapid burial best explains the preservation of the fossil grass (fig. 19*D–F*).

The boundary between buried lowland soil and overlying tideflat mud is typically sharp—evidence that the change from lowland to tideflat happened abruptly (figs. 17*C*, 22*A*, 22*C*, 23*B*). Erosion cannot have caused this abruptness while sparing fossil grass that stands rooted in buried soils (fig. 19).

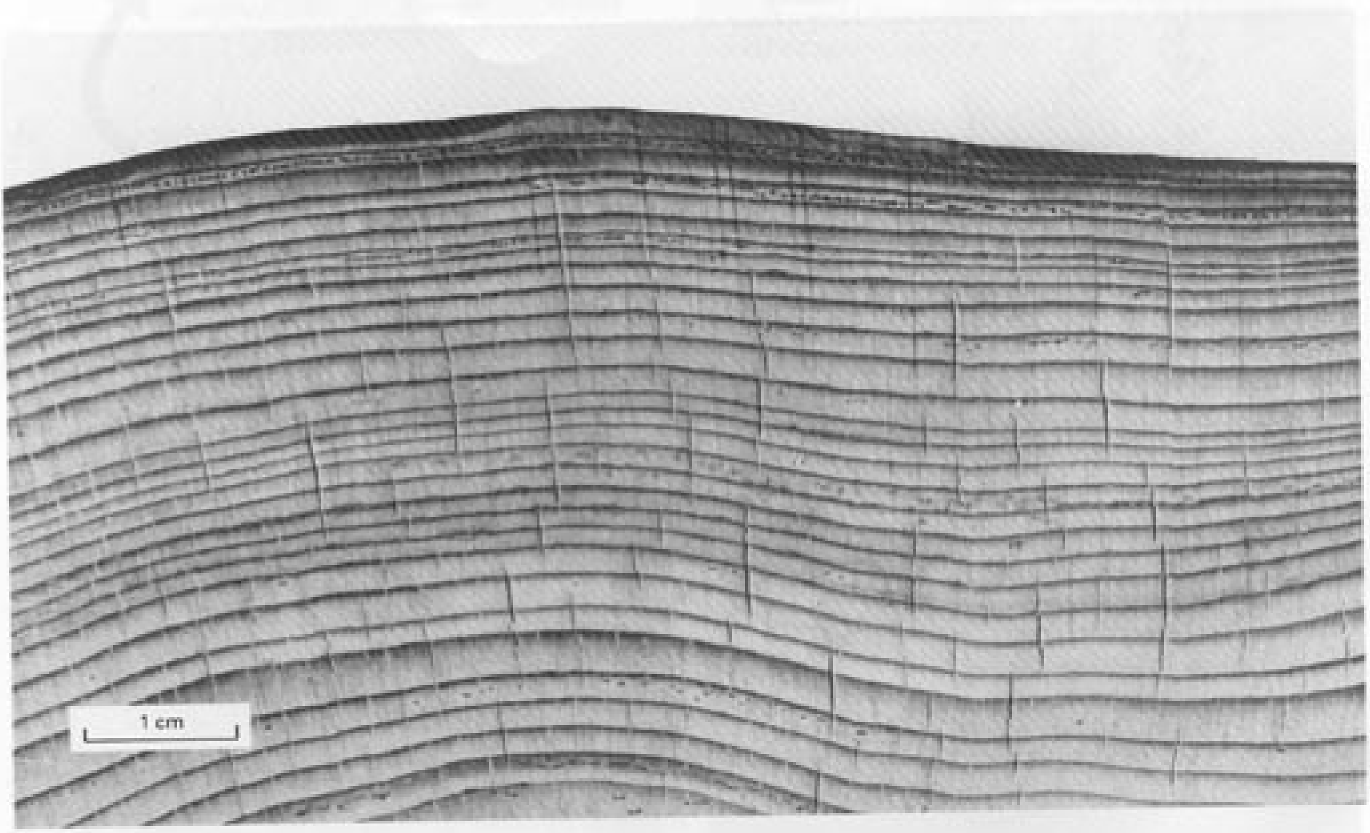


Figure 18. Outermost rings of a Sitka spruce stump rooted in the youngest buried lowland soil at Willapa Bay (fig. 17*A*, stump **b**). The outermost ring is stained from decay of the bark, which fell off during sampling.

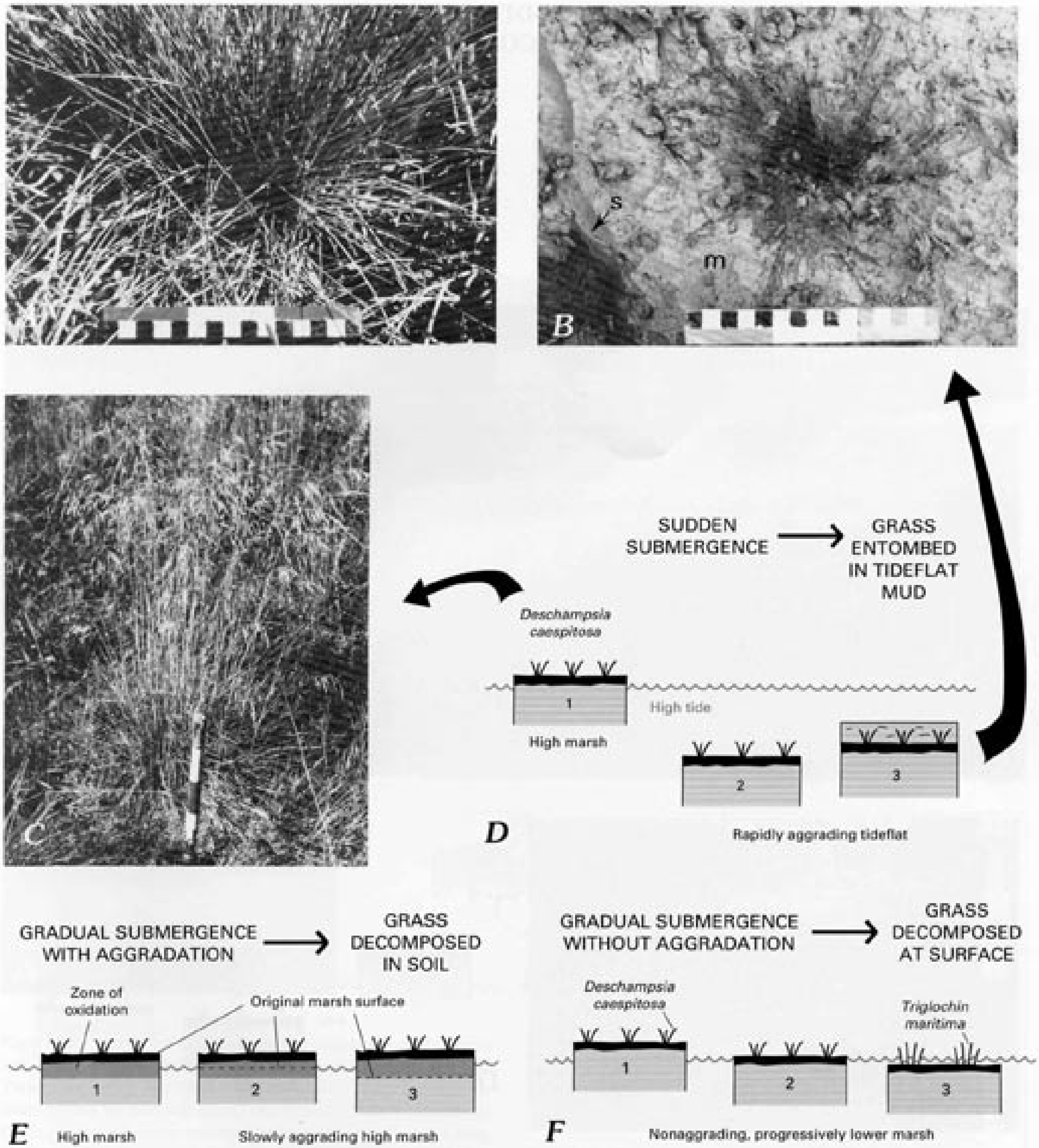
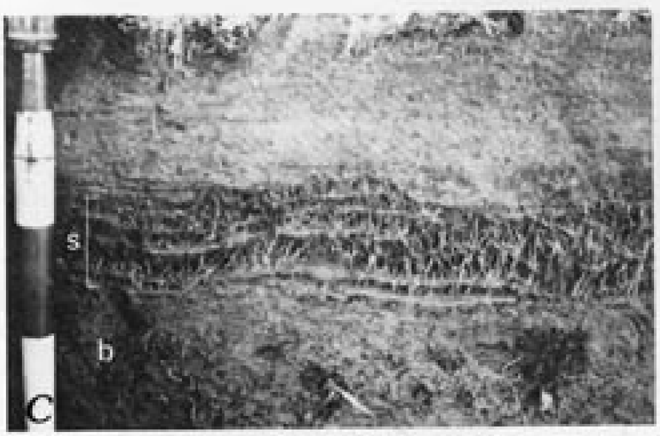


Figure 19. Modern and fossil leaves and stems of the tufted grass *Deschampsia caespitosa* at the Niawiakum River, Willapa Bay (Atwater and Yamaguchi, 1991, fig. 4). *A*, oblique closeup of tufted stems and leaves growing low on a modern plant. The scale is 15 cm long. *B*, vertical view of stems and leaves of a fossil grass tuft surrounded by tideflat mud (**m**). The scale is 15 cm long. The dark soil (**s**) in which the tuft is rooted lies 2–4 cm below most of the surface in view. The probable time of burial was between 1,400 and 1,900 years ago (soil **S**, figs. 24, 25). *C*, a modern plant. Stripes on the scale are 10 cm long. *D*, likely sequence of events that produced the fossil tuft in *B*. *E* and *F*, events unlikely to have produced the tuft shown in *B*.

TSUNAMIS FROM GREAT SUBDUCTION ZONE EARTHQUAKES CAN LEAVE SAND ON COASTAL LOWLANDS . . .

Because a great subduction-zone earthquake usually produces a tsunami (Abe, 1977), coastal lowlands in the region of the earthquake may receive sediment from the train of tsunami waves that comes ashore soon after the earthquake. Such onland deposition followed the 1960 Chile earthquake (Wright and Mella, 1963, p. 1389; Bourgeois and Reinhart, 1989). Near Maullín, Chile (fig. 10*B*), the tsunami-laid sand widely blankets the 1960 soil (fig. 20). The sand, mostly less than 10 cm thick, commonly contains the rooted stems and leaves of herbaceous plants around which the sand accumulated. Locally, the sand contains silty layers that may represent lulls between waves (fig. 20*C*).



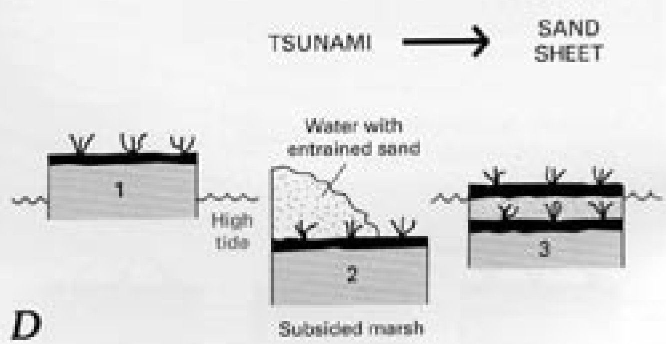
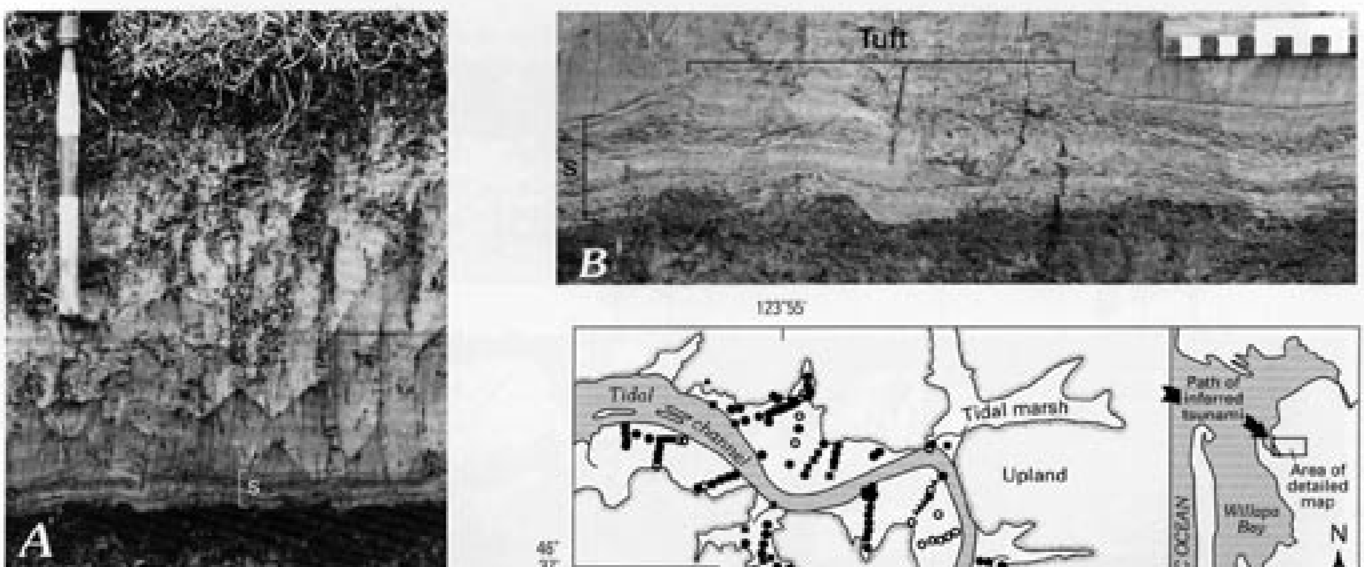


Figure 20. Sand deposited on lowlands near Maullín, Chile (fig. 10 *B*), by the tsunami from the 1960 Chile earthquake. Photographs taken in 1989. Stripes on handle in *B* and *C* are 10 cm long. *A*, two sand beds (lower right) on property of Juan Vera (left), who reported finding tsunami-laid sand in this area in 1960. The upper layer accumulated in 1960, the lower layer during an earlier tsunami. Río Ballenar locality of Atwater and others (1992). *B*, 1960 sand bed (**s**) etched by high tides along an eroding, otherwise peaty bank 1 km west-southwest of locality shown in *A*. *C*, lamination in the 1960 sand bed (**s**) near locality shown in *B*. Resistant laminae are silty, the sand having been etched by tides. Stringy, largely vertical features are roots. Buried 1960 soil (**b**) is not as dark as in *A* because tides have coated it with mud and algae. *D*, sequence of events that produced sandy tsunami deposits on Chilean lowlands in 1960.

. . . AND PROBABLY DID SO IN WASHINGTON AND OREGON

Some of the buried coastal soils in southern Washington and northern Oregon are mantled with sandy deposits probably left by tsunamis. Such deposits widely overlie the youngest buried soil (figs. 21, 22). The sand records an unusual event; relative to other sand above the soil, it is exceptionally coarse or thick or both. During the event, the sand moved landward, the direction in which the sand tapers (fig. 22*C*) (Atwater, 1992, fig. 2). Deposition of the sand was interrupted by lulls during which mud settled (fig. 22A, *B*). Deposition approximately coincided with sudden subsidence of the land, for the sandy interval surrounds rooted tufts of grass that lived on the soil at the time of subsidence (fig. 22*B*). Extraordinary, landward directed, interrupted by lulls, and approximately coincident with coastal subsidence in Washington, deposition of the sand is not easily credited to a flood or storm, or to a tsunami of remote origin. Rather, the sand implies a tsunami from an earthquake at the Cascadia subduction zone.

Figure 21. Sand bed (**s**) etched by high tides along the lower Salmon River, northern Oregon (fig. 12*A*) (Grant and McLaren, 1987). Probably analogous with the Chilean sand bed shown in figure 20*B*.



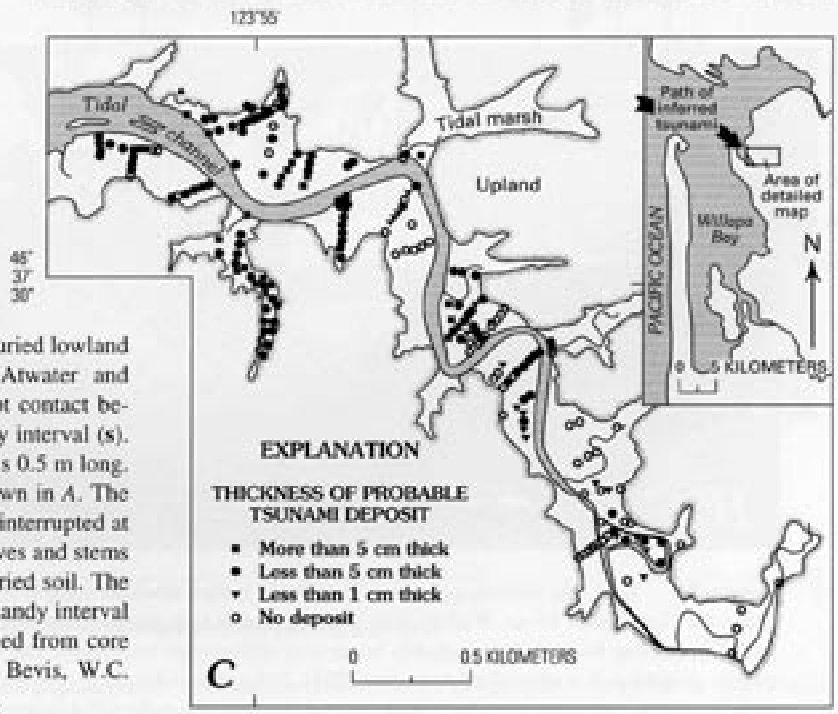


Figure 22. Sandy interval overlying the youngest buried lowland soil along the Niawiakum River, Willapa Bay (Atwater and Yamaguchi, 1991, fig. 5). *A*, outcrop showing abrupt contact between buried lowland soil (dark) and laminated sandy interval (**s**). Blade of shovel rests on modern tidal marsh; handle is 0.5 m long. *B*, detail of the left part of the sandy interval (s) shown in *A*. The lamina of sand and mud (compare with fig. 20*C*) are interrupted at center left, where they accumulated around tufted leaves and stems of *Deschampsia caespitosa* (fig. 19) rooted in the buried soil. The scale is centimeters. *C*, distribution and thickness of sandy interval shown in *A* (Reinhart and Bourgeois, 1987). Compiled from core logs and outcrop sketches by M.A. Reinhart, K.A. Bevis, W.C. Grant, B.F. Atwater, R.T. Versical, and S. McMullen.

CENTURIES COMMONLY ELAPSE BETWEEN GREAT EARTHQUAKES IN COASTAL WASHINGTON

Sequences of buried lowland soils give clues about how much time may elapse between successive great earthquakes in coastal Washington. The sequences shown in figures 23-25 suggest that the elapsed times commonly span hundreds of years. Earthquakes that incubated longest may be widely marked by peaty forest soils (**Y** and **S** in the figures) beneath which the buried soils (**U** and **N**, respectively) retain little organic matter. Prolonged uplift between earthquakes—the upward bulging in figure 9—may have allowed trees to colonize bold soil **Y** while admitting oxygen into organic matter of soil **U**, which thereby became faint; the same may be true for bold soil **S** and faint soil **N** (fig. 25).

There remain many challenges, however, in reconstructing the history of great earthquakes at the Cascadia subduction zone. One basic challenge is to show which buried soils correspond with great earthquakes, and vice versa. Buried soils at some sites may record nonseismic changes in tide levels, or earthquakes smaller than magnitude 8 (Nelson and others, 1996). Conversely, buried soils produced by great earthquakes may have disappeared in many places through decomposition after burial, as probably happened to soil **W** (figs. 23*B*, 25).

A further challenge is to place limits on earthquake size. Such limits have been sought through radiocarbon dating of earthquake-killed plants rooted in soil **Y** and its correlatives (Atwater and others, 1991; Nelson and others, 1995). The most precise of this dating limits the time of plant death to the same few decades close to A.D. 1700 in southern Washington, northern Oregon, and northern California. This finding can be explained by a swift series of magnitude-8 earthquakes. However, it also leaves standing the possibility of a single earthquake of magnitude 9.

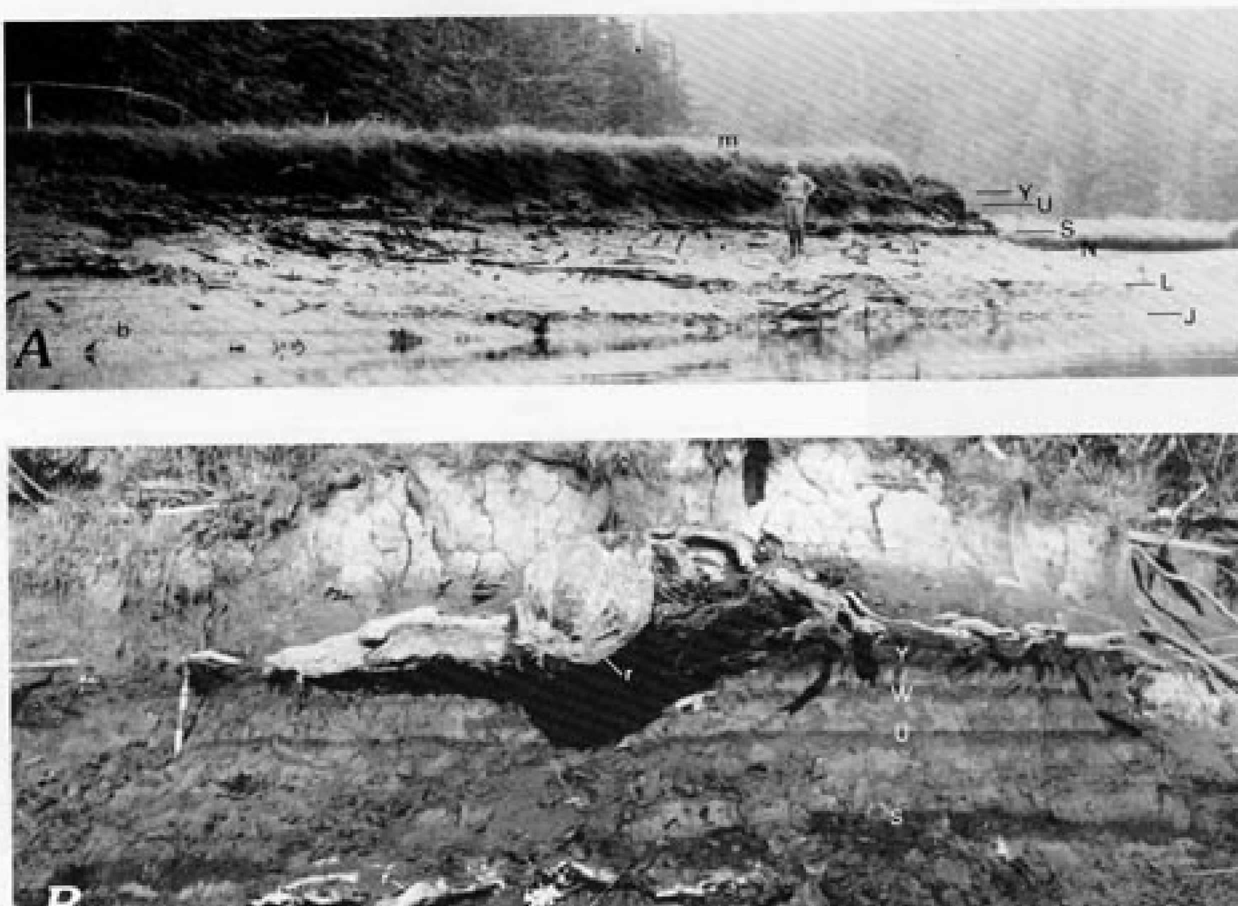


Figure 23. Low-tide outcrops showing successive buried lowland soils in southern coastal Washington. *A*, six buried soils along the Niawiakum River, Willapa Bay. Soils **U** and **N** lack organic matter resistant to erosion. Soils **J** and **L** descend away from Pleistocene bedrock (**b**), probably because of differential settlement. The modern marsh (**m**) extends to the forest, which covers an upland. Locality 17 of Atwater (1992). *B*, four buried soils at the mouth of Elliott Slough, Grays Harbor. Two of the soils contain spruce roots (**r**). The visible part of the shovel handle is 0.4 m long. Locality 9 of Atwater (1992).

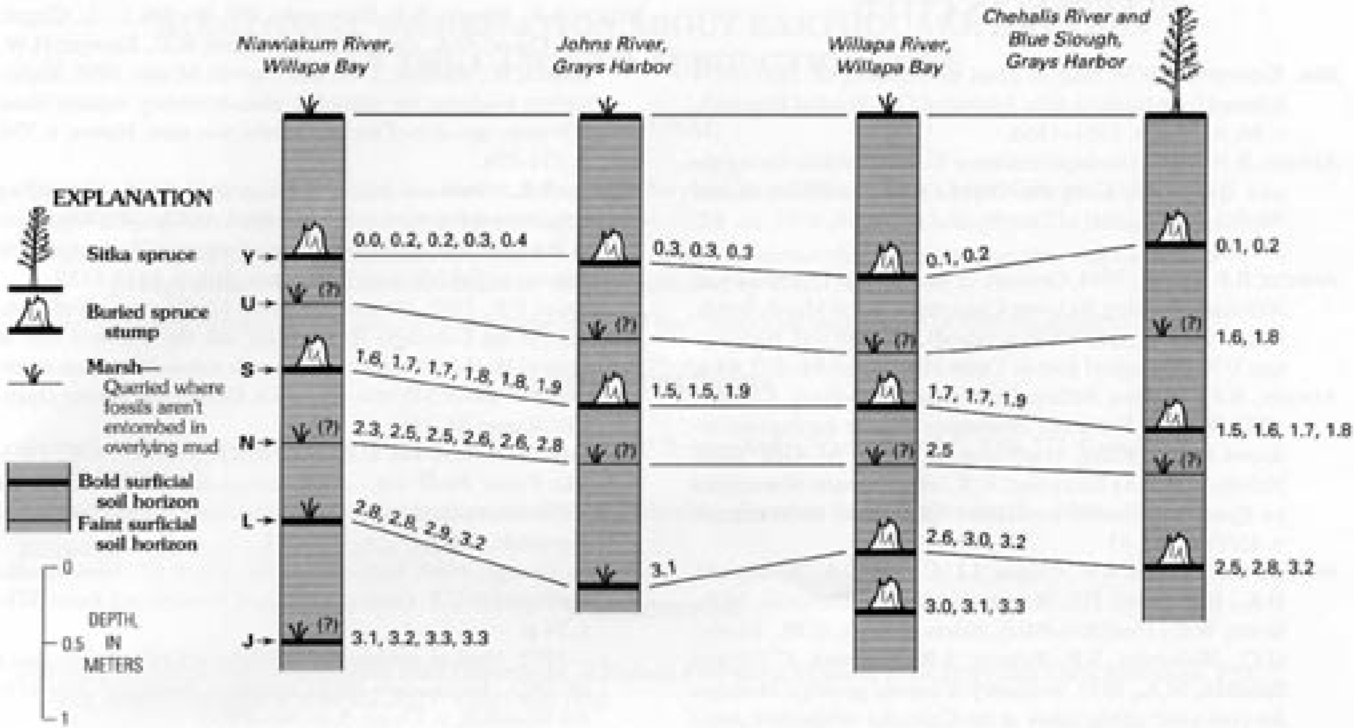


Figure 24. Sequences of buried lowland soils (bold letters) at Grays Harbor and Willapa Bay. The numbers are ages in thousands of radiocarbon years rounded to the nearest hundred. The standard deviation is probably 50–200 radiocarbon years for most ages. The ages were measured on woody roots, sticks, cones, and surficial horizons of soils. Lines between columns link soils that may record a single earthquake or a brief series of earthquakes. Localities of Atwater (1992), from left to right: 17; 14; 15; 10 and 11 combined.

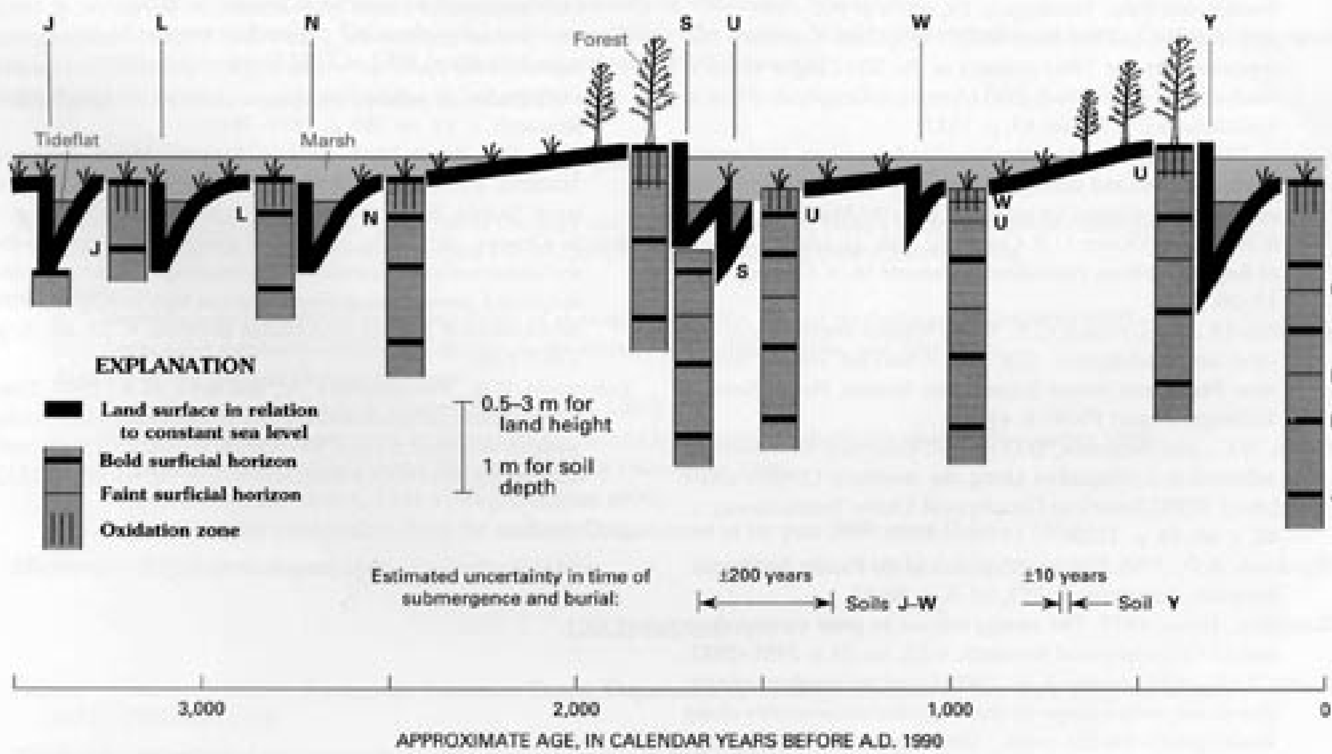


Figure 25. Inferred history of landscape, soils, and earthquakes at the Willapa Bay locality shown in figure 23*A*. Bold letters signify buried soil horizons. Soil **W** is hypothetical at this locality (Atwater, 1992).

REFERENCES CITED

Abe, Katsuyuki, 1979, Size of great earthquakes of 1837–1974 inferred from tsunami data: Journal of Geophysical Research, v. 84, no. B4, p. 1561–1568.

Atwater, B.F., 1992, Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington: Journal of Geophysical Research, v. 97, no. B2, p. 1901–1919.

Atwater, B.F., comp., 1994, Geology of liquefaction features about 300 years old along the lower Columbia River at Marsh, Brush, Price, Hunting, and Wallace Islands, Oregon and Washington: U.S. Geological Survey Open-File Report 94–209, 64 p.

Atwater, B.F., Jiménez Núñez, Héctor, and Vita-Finzi, Claudio, 1992, Net late Holocene emergence despite earthquake-induced submergence, south-central Chile, in Ota, Yoko, Nelson, A.R., and Berryman, K.R., eds., Impacts of tectonics on Quaternary coastal evolution: Quaternary International, v. 15/16, p. 77–85.

Atwater, B.F., Nelson, A.R., Clague, J.J., Carver, G.A., Yamaguchi, D.K., Bobrowski, P.T., Bourgeois, Joanne, Darienzo, M.E., Grant, W.C., Hemphill-Haley, Eileen, Kelsey, H.M., Jacoby, G.C., Nishenko, S.P., Palmer, S.P., Peterson, C.D., and Reinhart, M.A., 1995, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone: Earthquake Spectra, v. 11, no. 1, p. 1–18.

Atwater, B.F., Stuiver, Minze, and Yamaguchi, D.K., 1991, Radiocarbon test of earthquake magnitude at the Cascadia subduction zone: Nature, v. 353, no. 6340, p. 156–158.

Atwater, B.F., and Yamaguchi, D.K., 1991, Sudden, probably coseismic submergence of Holocene trees and grass in coastal Washington state: Geology, v. 19, no. 7, p. 706–709.

Bourgeois, Joanne, and Reinhart, M.A., 1989, Onshore erosion and deposition by the 1960 tsunami at the Rio Lingue estuary, south-central Chile [abs.]: EOS [American Geophysical Union Transactions], v. 70, no. 43, p. 1331.

Cooper, J.G., 1860, Report on the botany of the route, in Reports of explorations and surveys to ascertain the most practicable and economical route for a railroad from the Mississippi River to the Pacific Ocean: U.S. Congress, 36th, 1st session, House of Representatives, Executive Document 56, v. 12, book 2, p. 13–39.

Franklin, J.F., and Dyrness, C.T., 1973, Natural vegetation of Oregon and Washington: U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Forest Service Technical Report PNW–8, 417 p.

Grant, W.C., and McLaren, D.D., 1987, Evidence for Holocene subduction earthquakes along the northern Oregon coast [abs.]: EOS [American Geophysical Union Transactions], v. 68,), no. 44, p. 1239.

Hyndman, R.D., 1995, Giant earthquakes of the Pacific Northwest: Scientific American, v. 273, no. 6, p. 50-57.

Kanamori, Hiroo, 1977, The energy release in great earthquakes: Journal of Geophysical Research, v. 82, no. 20, p. 2981–2987.

Kunze, L.M., and Cornelius, L.C., 1982, Baseline inventory of rare, threatened and endangered plant species/communities along Washington's Pacific coast: Washington Natural Heritage Program, Coastal Zone Management Grant No. G82–029, Washington Department of Ecology (Olympia, WA 98504–8711), 164 p.

Nelson, A.R., Atwater, B.F., Bobrowsky, P.T., Bradley, L.-A., Clague, J.J., Carver, G.A., Darienzo, M.E., Grant, W.C., Krueger, H.W., Sparks, R., Stafford, T.W., and Stuiver, Minze, 1995, Radiocarbon evidence for extensive plate-boundary rupture about 300 years ago at the Cascadia subduction zone: Nature, v. 378, p. 371-374.

Nelson, A.R., Shennan, Ian, and Long, A.J., 1996, Identifying coseismic subsidence in tidal-wetland stratigraphic sequences at the Cascadia subduction zone of western North America: Journal of Geophysical Research, v. 101, p. 6115-6135.

Obermeier, S.F., 1995, Preliminary limits for the strength of shaking for the Columbia River valley and the southern half of coastal Washington for the Cascadia subduction zone earthquake of about 300 years ago: U.S. Geological Survey Open-File Report 94–589.

Ovenshine, A.T., Lawson, D.E., and Bartsch-Winkler, S.R., 1976, The Placer River Silt—An intertidal deposit caused by the 1964 Alaska earthquake: U.S. Geological Survey Journal of Research, v. 4, no. 2, p. 151–162.

Plafker, George, 1969, Tectonics of the March 27, 1964, Alaska earthquake: U.S. Geological Survey Professional Paper 543–I, 74 p.

———1972, Alaskan earthquake of 1964 and Chilean earthquake of 1960—Implications for arc tectonics: Journal of Geophysical Research, v. 77, no. 5, p. 901–925.

Plafker, George, and Savage, J.C., 1970, Mechanism of the Chilean earthquakes of May 21 and 22, 1960: Geological Society of America Bulletin, v. 81, no. 4, p. 1001–1031.

Reinhart, M.A., and Bourgeois, Joanne, 1987, Distribution of anomalous sand at Willapa Bay, Washington—Evidence for large-scale landward-directed processes [abs.]: EOS [American Geophysical Union Transactions], v. 68, no. 44, p. 1469.

Thatcher, Wayne, and Rundle, J.B., 1984, A viscoelastic coupling model for the cyclic deformation due to periodically repeated earthquakes at subduction zones: Journal of Geophysical Research, v. 89, no. B9, p. 7631–7640.

Weinmann, F.C., Boulé, Mark, Brunner, Kenneth, Malek, John, and Yoshino, Victor, 1984, Wetland plants of the Pacific Northwest: Seattle, Wash., U.S. Army Corps of Engineers, 85 p.

Wright, Charles, and Mella, Arnoldo, 1963, Modifications to the soil pattern of south-central Chile resulting from seismic and associated phenomena during the period May to August 1960: Seismological Society of America Bulletin, v. 53, no. 6, p. 1367–1402.

Yamaguchi, D.K., Woodhouse, C.A., and Reid, M.S., 1989, Tree-ring evidence for synchronous rapid submergence of the southwestern Washington coast 300 years B.P. [abs.]: EOS [American Geophysical Union Transactions], v. 70, no. 43, p. 1332.

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ADDITIONAL INFORMATION ABOUT EARTHQUAKE HAZARDS AT THE CASCADIA SUBDUCTION ZONE

REGIONAL

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- Geologic evidence of shaking: liquefaction features in Alaska from the 1964 earthquake. 80 pages

Maps

- Areas where sand and silt may liquefy (lose strength) in valleys between Renton and Puyallup
- Areas most subject to earthquake damage in the vicinity of Vancouver, Washington

Lists of reports and maps. On earthquake and tsunami hazards in western Washington and adjacent areas. Compiled for publications dated 1855 to 1991 (earthquakes) and up to 1994 (tsunamis)

Electronic—http://www.geophys.washington.edu/SEIS/

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- Areas most subject to earthquake damage in the vicinity of Portland, Salem, and Siletz Bay

Articles in the journal *Oregon Geology*

- Preparing for earthquakes in Oregon (March/April 1997)
- Expected financial losses from building damage caused by severe earthquakes in Oregon (November 1996)
- Liquefaction susceptibility in the Willamette Valley (November 1996)
- Oregon earthquake history, 1841-1994 (November 1995)
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