PROBABLE LOCAL PRECEDENT FOR EARTHQUAKES OF MAGNITUDE 8 OR 9 IN THE PACIFIC NORTHWEST

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Great earthquakes probably can happen in the Pacific Northwest. Such earthquakes, being of magnitude 8 or 9, would release as least as much energy as did the 1906 San Francisco earthquake. Their source would be the plate-bounding fault that descends gently eastward beneath the continental margin from southern British Columbia to northern California. This huge fault, the Cascadia subduction zone (fig. 1a), is not known to have produced great earthquakes in the 200 years since white people arrived in the Pacific Northwest. But Cascadia has much in common with subduction zones elsewhere on which great earthquakes have occurred historically (Heaton and Hartzell, 1987). Moreover, as reviewed in this report, great earthquakes seem to have occurred on the Cascadia subduction zone itself--at least twice in the past 1700 years.

COASTAL EVIDENCE FOR THE PAST OCCURRENCE OF GREAT CASCADIA EARTHQUAKES

If great earthquakes have occurred on the Cascadia subduction zone during the past 1700 years, evidence of the earthquakes should abound on the Northwest coast. This is chiefly because a great subduction-zone earthquake usually causes the adjoining coast to undergo meters of uplift or subsidence. The uplift can result in the permanent emergence of wave-cut coastal benches; the subsidence can cause the estuarine burial of well-vegetated coastal lowlands that drop to the level of tideflats. In addition, coastal lowlands may preserve anomalous bodies of sand that result from shaking during the earthquake and from the tsunami that comes ashore minutes later.

Earth scientists have barely begun to ask whether all these great-earthquake telltales are present on the Northwest coast. But in just the past two years they have found much evidence for rapid subsidence, some evidence for consequent tsunamis, and a little evidence for uplift and shaking.

Subsidence. That great Cascadia earthquakes probably have occurred is indicated chiefly by evidence of sudden coastal subsidence. This evidence takes the form of marshes that have been buried by tidal mud. First recognized in the Northwest in 1986, such buried marshes are now known to range in location from southernmost British Columbia to northern California (Rogers, 1988; Atwater, 1987, 1988; Grant and McLaren, 1987; Darienzo and Peterson, 1987; Nelson, 1987; G.A. Carver, oral commun., 1988). Simple tests can eliminate storms, floods, far-traveled tsunamis, differential compaction, and global sea-level rise as alternative explanations for the marshland burial (Atwater, 1987, p. 943).

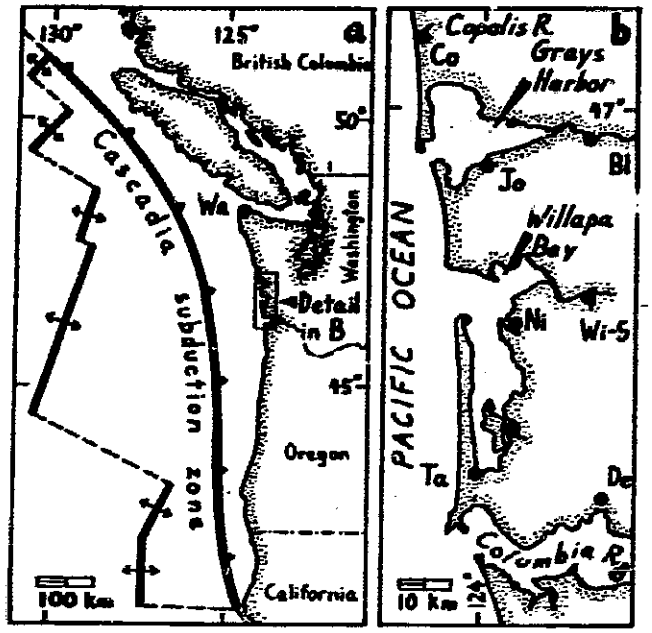

Fig. 1. Index maps. (a), Cascadia subduction zone. (b), coastal southwestern Washington.

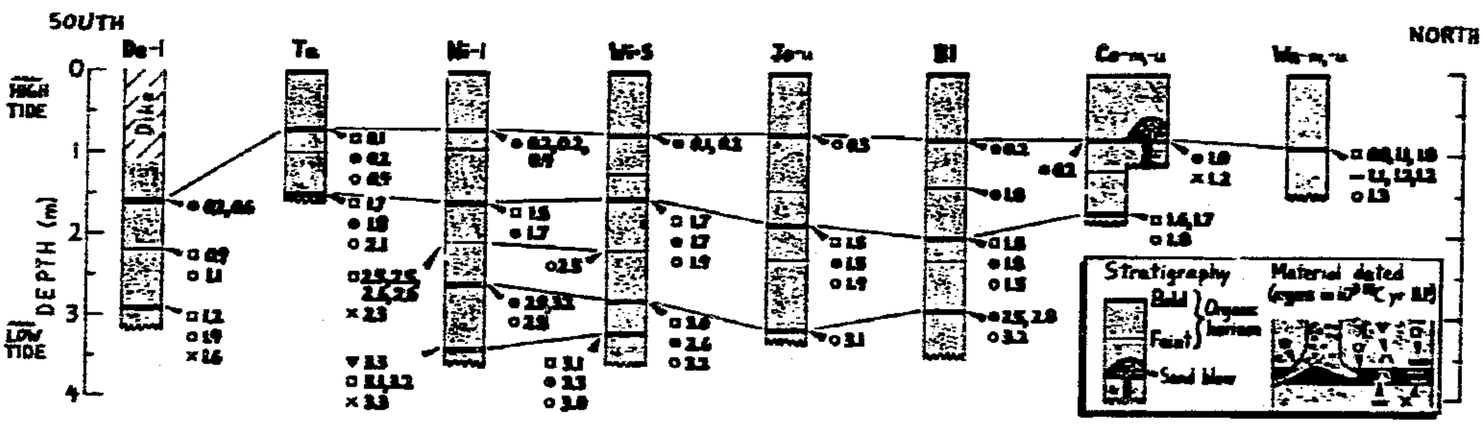

Fig. 2. Organic horizons and radiocarbon ages of buried-wetland soils in coastal Washington (Atwater, 1988). Solid lines between columns denote correlations among radiocarbon-dated soils. Localities (letter symbols at top) keyed to figure 1 and to tables of Atwater (1988). Material dated, with stratigraphic position shown at lower right: (●) root of tree, chiefly Sitka spruce; (▼), (▬) rhizome [below-ground stem] of <u>Triglochin maritima</u>, a grass-like tidal-marsh plant; (◘), (✖) stick(s) or cones or both; (○) uppermost 0.5 or 1.0 cm of organic horizon.

At least in southwestern Washington, jerky coastal subsidence probably had too much areal extent to be explained by anything other than great Cascadia earthquakes. A great Cascadia earthquake is likely to entail subsidence of a coastal strip at least 100 km long and tens of kilometers wide (Atwater, 1987). Subsidence on that scale is suggested by regionality in the sequence and radiocarbon age of buried marshland soils in southwestern Washington (figs. 1b, 2). This regionality implies that at least two jerks of subsidence--one about 300 years ago[1], the other about 1700 years ago--involved a coastal strip no less than 85 km long and no less than 30 km wide.

It is remotely possible that each correlated soil in figure 2 represents a series of moderate earthquakes that successively jerked adjoining areas during an interval too brief to dissect by conventional radiocarbon dating. This possibility is now being tested by the tree-ring dating of cedars that died from sudden subsidence into the intertidal zone about 300 years ago (D.K. Yamaguchi, written commun., 1988).

Tsunami. Tsunamis probably resulted from at least some of the events that jerked the coast downward in Washington and Oregon. The evidence for tsunamis consists of sand that locally veneers some of the buried coastal marshes (Atwater, 1987; Reinhart and Bourgeois, 1987; Grant and McLaren, 1987). This sand is typically coarser than other intertidal deposits in the vicinity. Landward thinning of the sand indicates deposition by surge from a bay or from the sea. About 300 years ago in southwestern Washington, the sand from such a surge entombed the rooted stems and leaves of grass that had been living on the marsh when the marsh was jerked downward. This relation indicates that the surge took place within a few years of the jerk. Such coincidence, though unlikely for storms or far-traveled tsunamis, would be expected of tsunamis from great Cascadia earthquakes.

It remains conceivable that storms or seiches caused the surges from which the sand was deposited. These alternatives are now being tested through inference of the duration, depth, and velocity of the surges (M.A. Reinhart and Joanne Bourgeois, written commun., 1988).

Uplift. Analogies with uplift at other subduction zones imply that great Cascadia earthquakes would produce elevated shorelines on the Northwest coast (West and McCrumb, 1988), particularly where a subduction-zone rupture extends beneath the coast. Two candidates have been identified thus far (fig. 1)--one a beach gravel containing 3000-year-old wood in southern Oregon (Kelsey and others, 1988), the other a wave-cut bench perhaps 1000 years old in northern California (G.A. Carver, oral commun., 1988). These poorly understood features may record Cascadia earthquakes whose ruptures splayed upward into subsidiary faults. As shown by Kelsey and Carver (1988), faults probably rooted in the Cascadia

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1 All ages in text are in sidereal years; calibration of radiocarbon ages follows Stuiver and Pearson (1986) and Pearson and Stuiver (1986).

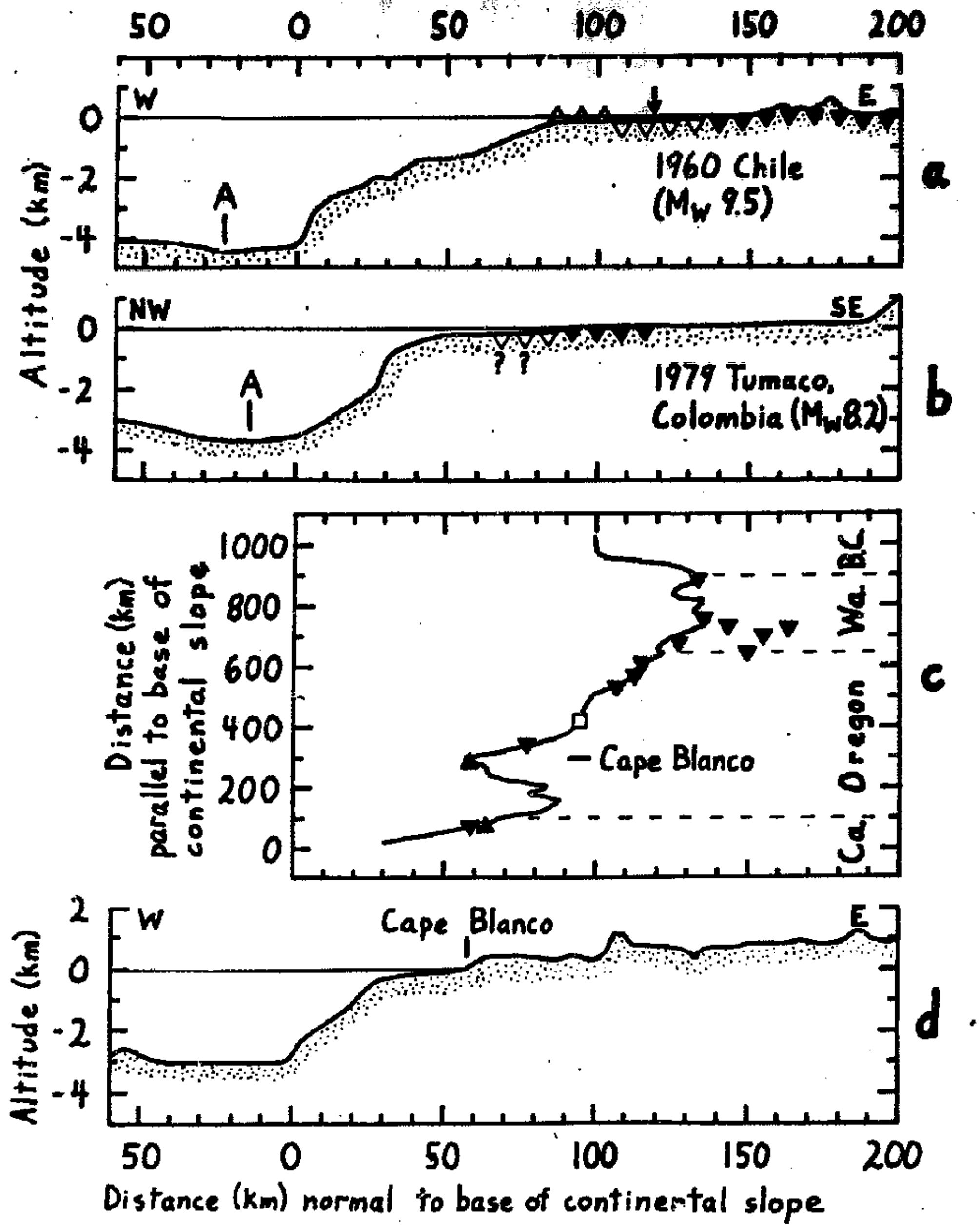

Fig. 3. Bathymetry and coseismic deformation versus distance from base of continental slope. Triangles point in direction of coseismic vertical movement; open triangles denote offshore movement, queried where doubtful. Moment magnitudes (M_w) from Kanamori (1977) and Kanamori and McNally (1982). A, axis of trough or channel. (a) Profile S82E through Valdivia, Chile. Bathymetry from Prince (1980). Coseismic deformation from Plafker and Savage (1970); arrow shows projected location of coseismically subsided coast 17 km SSW of profile. (b) Profile S53E through San Juan, Colombia (Herd and others, 1981). (c) Shoreline location between central Vancouver Island (top) and Cape Mendocino (bottom). Triangles show sites evincing coseismic subsidence or uplift of late Holocene age (Darienzo and Peterson, 1987; Grant and McLaren, 1987; Nelson, 1987; Atwater, 1988; Kelsey and others, 1988; G.A. Carver, oral commun., 1988). Square denotes site with evidence for only gradual coastal submergence (Nelson, 1987). (d) East-west profile through Cape Blanco. Bathymetry from National Ocean Survey (1974).

subduction zone come ashore in northern California. The most recent thrusting on at least one of these faults occurred about 300 years ago (Carver and Burke, 1987). Kelsey and Carver (1988) liken northern California to the Gulf of Alaska, where thrusting on subsidiary faults produced a complex pattern of uplift, and may have also caused local subsidence, during the great (magnitude 9.2) Alaskan earthquake of 1964 (Plafker and Ruben, 1978, p. 706, 721).

Youthful uplifted terraces are scarce or absent on the coast of northern Oregon and Washington (West and McCrumb, 1988), probably because these areas undergo only subsidence during great Cascadia earthquakes. By analogy with the 1960 Chile earthquake (magnitude 9.5) and the 1979 Tumaco, Colombia earthquake (magnitude 8.2), uplift might be chiefly confined to areas within 105 km (Chilean analogy) or 90 km (Colombian analogy) of the base of the continental slope (fig. 3a, b). At such distances, little or no coseismic uplift would occur along the northern quarter (Chilean analogy) or northern half (Colombian analogy) of the Oregon coast (fig. 3c). Even Cape Blanco (fig. 3c, d) could escape coseismic uplift if the Colombian analogy applies and if, as seems likely (Herd and others, 1979), the Colombian subsidence extended tens of kilometers offshore (fig. 3b).

<u>Shaking.</u> The published case for great Cascadia earthquakes includes no compelling evidence that shaking accompanied the jerks of coastal subsidence. The strongest known hint is vented sand, containing clasts of the mud through which it rose, that buried part of a spruce woodland in coastal southwestern Washington about 1000 years ago (sand blow at site Co-u, fig. 2). The venting, indicative of strong shaking, does not seem to have accompanied subsidence of the woodland, or of coastal southwestern Washington regionally. But rapid subsidence did occur about 1000 years ago in northwesternmost Washington and, perhaps, near the mouth of the Columbia River (site De-1, fig. 2). Only by this kind of permissive correlation does shaking seem have accompanied a jerk of coastal subsidence in the Pacific Northwest.

The hypothesis of shaking during subsidence needs to be tested wherever easily vented sand underlies subsided wetlands that are well exposed in cross section. Few such places exist in coastal southwestern Washington. Additional evidence of shaking could take the form of landslides, provided that wet weather and non-Cascadia earthquakes can be excluded as triggers.

CONCLUSIONS

Earth scientists have recently begun to study ancient subsidence, uplift, tsunamis, and shaking as clues to the seismic potential of the Pacific Northwest. The little work done so far shows that great earthquakes probably have occurred on the Cascadia subduction zone in the recent pre-white-man past. Particularly suggestive is the widespread evidence for sudden coastal subsidence and accompanying tsunamis. This evidence implies local precedent for the future occurrence of great earthquakes in the Pacific Northwest.

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