Reports

Evidence for Great Holocene Earthquakes Along the Outer Coast of Washington State

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Intertidal mud has buried extensive, well-vegetated lowlands in westernmost Washington at least six times in the past 7000 years. Each burial was probably occasioned by rapid tectonic subsidence in the range of 0.5 to 2.0 meters. Anomalous sheets of sand atop at least three of the buried lowlands suggest that tsunamis resulted from the same events that caused the subsidence. These events may have been great earthquakes from the subduction zone between the Juan de Fuca and North America plates.

Geologic history could offer valuable constraints on the probability of a great (magnitude about 8 or 9) earthquake in the Pacific Northwest. Analogies with other subduction zones suggest that great earthquakes could emanate from the Cascadia subduction zone (Fig. 1), in which the Juan de Fuca plate has slipped beneath the North America plate at an average Quaternary rate of 3 to 4 cm per year (*1*). But no earthquake of the past 150 to 200 years in the states of Washington or Oregon has exceeded magnitude 7.5 (*2*), and Indian legends seem too ambiguous to indicate whether great Northwest earthquakes occurred before that time (*1*). Only geologic evidence is likely to reveal whether great earthquakes from the Cascadia subduction zone have occurred and, if they did, whether enough time has elapsed since the last event for another to be expected soon.

In this report I consider Cascadia's seismic potential in light of geologic evidence for recurrent coastal subsidence. This approach, new to the Pacific Northwest and seldom used elsewhere, yields strong evidence that great earthquakes have occurred in the Cascadia subduction zone during the past 10,000 years (the Holocene) (*3, 4*).

Coastal subsidence commonly accompanies a great subduction earthquake. The coseismic subsidence, in a chiefly onshore belt flanked by a mostly offshore zone of coseismic uplift, apparently results from elastic extension within and behind the seaward-lurching part of the continental plate (*5, 6*). Washington's outer coast conceivably could undergo either uplift or subsidence during a great Cascadia earthquake (Fig. 2). But westernmost Washington apparently lacks Holocene marine terraces indicative of coseismic uplift (*7*). Therefore, any great Cascadia earthquake of Holocene age most likely entailed coseismic subsidence in the present vicinity of Washington's outer coast.

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Subsidence during great subduction earthquakes in Chile (1960) and in Alaska (1964) changed vegetated coastal lowlands into barren estuarine flats, particularly where the subsidence was augmented by shaking-induced settlement (*8, 9*). At the head of Cook Inlet near Portage (Fig. 2), estuarine silt buried 18 km^2 of pre-earthquake lowland that had subsided 1.6 m and settled an additional 0.8 m in 1964 (*10*). Aggradation [1 to 2 m (*10*)] and uplift [0.2 to 0.3 m (*11*)] after 1964 have allowed lowland shrubs and trees to become reestablished in this area (*12*). A bed of estuarine mud that abruptly overlies a lowland soil and passes gradually upward into another lowland soil may thus indicate a cycle of coseismic submergence and postseismic shoaling. Accordingly, in Chile and Alaska, rhythmic alternation between estuarine mud and buried lowland soils has been cited as evidence of ancient subduction earthquakes (*10, 13, 14*).

Similar rhythmic bedding abounds in estuarine deposits of late Holocene age near Washington's outer coast. Peaty layers representing well-vegetated lowlands alternate rhythmically with muddy intertidal deposits at all of the estuaries that I studied, both large (Columbia River, Willapa Bay, and Grays Harbor) and small (Copalis River and Waatch River). The minimum number of buried lowlands per estuary ranges from one to six (Fig. 1), increasing with the depth to which Holocene intertidal deposits extend. Typically, the peaty layers are 0.05 to 0.20 m thick and the intervening intertidal deposits are 0.5 to 1.0 m thick. As exemplified at Willapa Bay (Fig. 3), the typical peaty layer consists of peaty mud that resembles the A

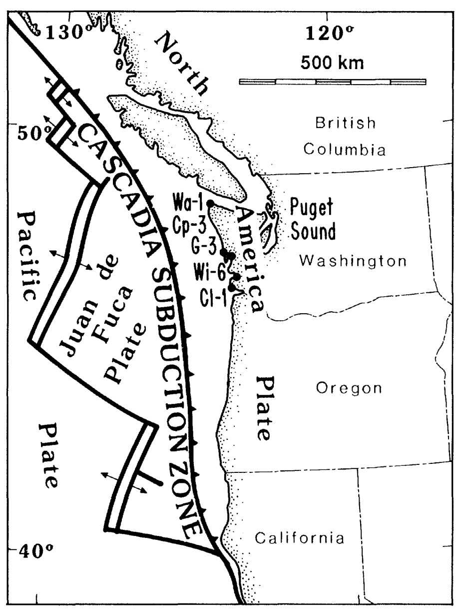

Fig. 1. Index map. Alphanumeric symbols give minimum numbers of widely buried coastal lowland surfaces of Holocene age. Cl, Columbia River (study area at 46°18.6′N, 124°57.88′W); Cp, Copalis River (47°07.1′N, 124°09.9′W); G, Grays Harbor (47°01.78′N, 124°01.47′W); Wa, Waatch River (48°21.41′N, 124°37.96′W); Wi, Willapa Bay (Fig. 3). Spreading ridge (symbol), transform fault (—), and subduction zone (symbol; barbs show direction of dip).

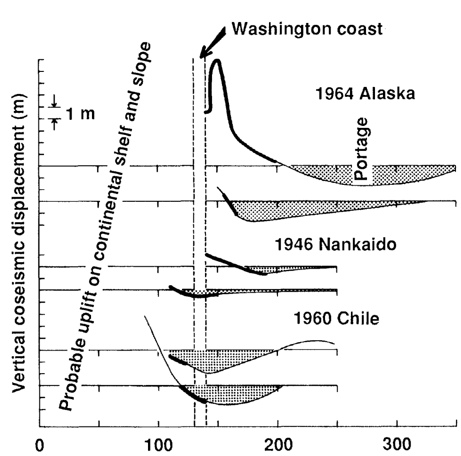

Fig. 2. Profiles of vertical coseismic displacement in south-central Alaska (*8*), southwest Japan (Nankaido) (*19*), and south-central Chile (*9*). Two profiles are shown for each earthquake. Subsidence is highlighted by shading; displacement equals zero where profile line intersects horizontal line. Thickened part of profile line shows location of outermost coast (small offshore islands excluded) in vicinity of profile. The moment magnitude (M_w) from Kanamori (*23*) and the length of belt of coseismic subsidence (L) are as follows: Alaska (M_w, 9.2; L, 950 km), Nankaido (M_w, 8.1; L, 300 km), and Chile (M_w, 9.5; L, >800 km). The arrow indicates the projected position of estuarine marshes near the outer coast of Washington State. Inferred uplift on shelf and slope pertains to all profiles. The distance represented between adjoining pairs of tick marks on the vertical axis is 1 m.

or O horizon of the soil on broad, rarely inundated parts of modern tidal marshes in the area. Conifer stumps rooted in buried peaty layers near uplands and streams confirm that the peaty layers represent nearly supratidal conditions. The bed above a typical peaty layer at Willapa Bay has an abrupt base but grades upward, from soft gray mud through firm mottled mud, into the succeeding peaty layer. The soft gray mud contains injected rhizomes (below ground plant stems) of only *Triglochin maritima*. At modern Willapa Bay this shallowly rooted plant is dominant only in salt-affected intertidal settings that are 0.5 to 2.0 m lower than the high-level tidal marsh represented by the typical peaty layer (Fig. 3C). The superposition of *T. maritima* mud over a peaty layer consequently indicates at least 0.5 m of submergence, and the sharpness of that contact indicates that the submergence was rapid. Conversely, the upward gradation from mud into a succeeding peaty layer implies at least 0.5 m of relatively gradual shoaling and the consequent building of a new high-level marsh. Thus Washington's outer coast has undergone submergence and shoaling in cycles that resemble, at least superficially, the known and inferred cycles of coseismic submergence and postseismic shoaling in great-earthquake regions of Alaska and Chile.

Three points tend to confirm that great subduction earthquakes triggered the cycles of submergence and shoaling in Washington.

1) Nothing other than rapid tectonic subsidence readily explains the burial of the peaty layers. Deposition during floods and storms should promote emergence of a coastal lowland, not submergence to the level of *T. maritima* salt marshes. Filled tidal creeks commonly produce bodies of sediment that are thicker and less conformable than the mud beds that buried the lowlands (Fig. 3C). Shaking-induced settlement, although consistent with the sagging of peaty layers and thickening of intertidal mud over the soft Holocene fill of a Pleistocene valley, does not explain why intertidal mud buries the peaty layers where they lap onto stiff Pleistocene deposits of the valley's sides (Fig. 3, B and C). Purely isostatic and eustatic submergence during the late Holocene should have been sufficiently gradual to permit the high parts of tidal marshes to build apace with rising relative sea level, thereby producing homogeneous tidal-marsh peat many meters thick. Such peat is present on many mid-latitude coasts (*15*), Puget Sound included (*16*), but not at the sites that I studied within 20 km of Washington's outer coast. Late Holocene submergence along Washington's outer coast was punctuated by jerks of tectonic subsidence that prevented the continuous maintenance of high-level tidal marshes.

2) Tsunamis probably coincided with at least three of the episodes of rapid tectonic subsidence. A great subduction earthquake usually produces a great tsunami (*17*). The tsunami from the great 1960 Chile earthquake deposited sheets of sand on two or more Chilean lowlands in the belt of coseismic subsidence (*13*). Similarly at Willapa Bay, a thin sandy interval mantles each of at least three buried lowlands among otherwise sand-free deposits. The most accessible of these sandy intervals forms a sheet (maximum thickness, 7 cm) that extends 3 km up the valley from the bayward edge of the buried marsh surface that it covers. This sheet disappears landward (Fig. 3B) and also becomes generally thinner and finer grained in that direction—a sign of a bayward source (Fig. 3A). Found only on buried lowlands, the sheet-like sandy intervals do not imply great storms or exotic tsunamis, for these events need not coincide with rapid tectonic subsidence at Willapa Bay. But approximate coincidence with Willapa Bay subsidence should be expected of

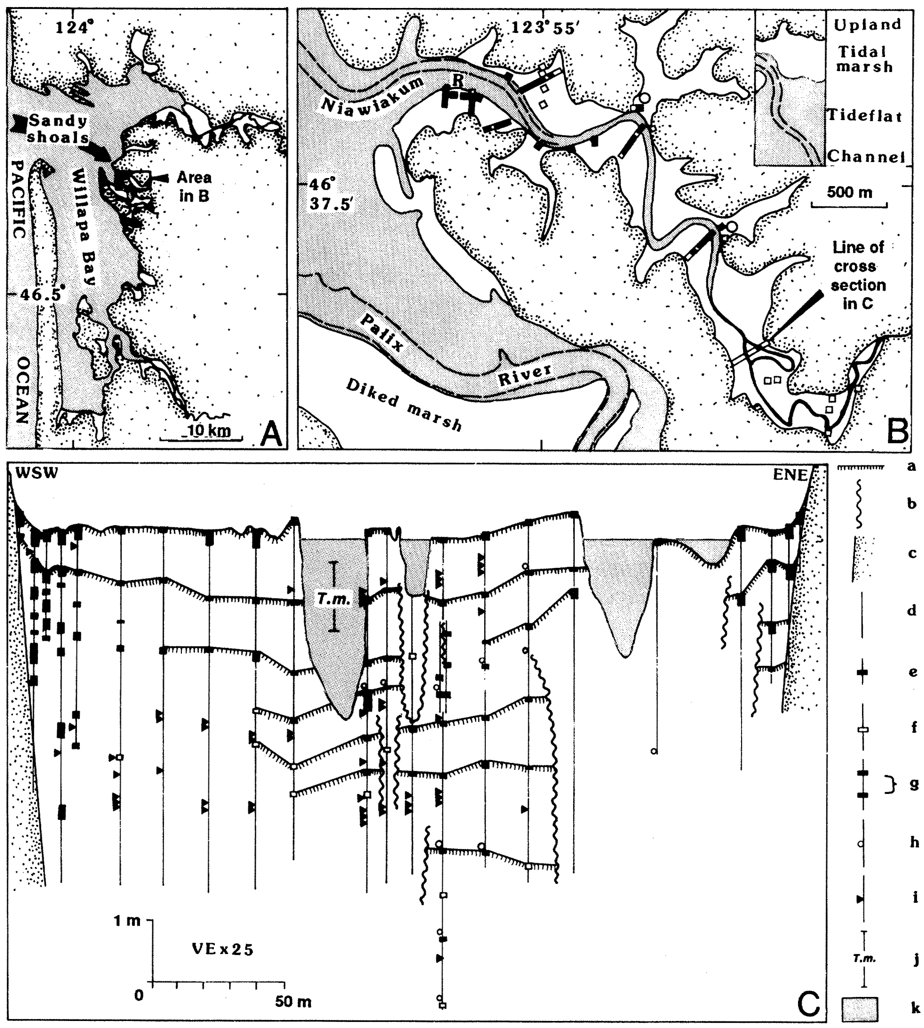

Fig. 3. Willapa Bay. (**A**) Index map. Arrow shows a path of the tsunamis that are inferred from sandy intervals atop buried lowlands in (B) and (C). Location of sandy shoals from Clifton (*24*). (**B**) Study area. Open circle, outcrop showing onlap of stiff Pleistocene deposits by buried peaty layers. Sandy interval atop uppermost buried peaty layer in cores and outcrops: present (closed square, single site; or rectangle, multiple sites); absent (open square or rectangle). (**C**) Cross section from correlated cores. Abbreviations: VE, vertical exaggeration; a, well-vegetated lowland—shape of modern surface determined by leveling; buried lowlands shown only where soils can be correlated with confidence on the combined bases of depth, serial order, position with respect to sandy intervals, and presumption of the same lateral continuity that is evident in low-tide outcrops; b, former margin of tidal creek—bounds body of soft mud; c, side of Pleistocene valley (line denotes top of Pleistocene deposits); d, borehole made with half-cylinder corer 1 m long and 2 cm in diameter; e, peaty layer—woody where thick near upland; f, contact akin to top of peaty layer—soft mud over firm mud; g, intertidal mud—typically stiffens upward between peaty layers; h, sandy interval—contains very fine sand and coarse silt in planar layers mutually separated by mud; i, fossil rhizome of *T. maritima*; j, zone in which *T. maritima* is the dominant living plant; k, water—top approximates mean higher high water, floor of deepest channel is near mean lower low water; ENE, east-northeast; WSW, west-southwest.

tsunamis from great earthquakes in the Cascadia subduction zone.

3) Tectonic subsidence during great subduction earthquakes could reconcile rates of short-term uplift with rates of long-term uplift in westernmost Washington. The uplift measured at tide gages and bench marks (2 to 3 mm per year average during the past 50 years) is much faster than that inferred from Pleistocene marine terraces (<0.5 mm per year average during the past ~100,000 years) (*18*). But these rates need not conflict if, as part of cyclic earthquake-related deformation (*19*), coseismic subsidence (like that inferred from the buried lowlands) has nearly negated cumulative interseismic uplift (of which tide-gage and bench-mark uplift would be a modern sample).

Jerky Holocene submergence at Washington estuaries thus strengthens the hypothesis that a future great earthquake could emanate from the Cascadia subduction zone. The number and shallow depth of buried lowlands at Willapa Bay (Fig. 3C) may mean that at least six such earthquakes have occurred since sea level approached its present position on mid-latitude coasts, that is, since 7000 years ago (*20*). The earthquake ruptures, if really from events of magnitude 8 or greater, should have extended coastwise for at least 100 km (*21*). This corollary can be tested by determining the coastwise extent of individual episodes of coseismic subsidence. Another testable corollary is that shaking during the postulated earthquakes should have caused the liquefaction of Holocene coastal-lowland sand (*22*). If buried lowlands prove coeval for coastwise distances greater than 100 km, and if sand proves to have vented onto some of these lowlands at the start of burial, then the chronology of jerky submergence could be used to constrain the current probability of a great subduction earthquake in the Pacific Northwest.

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Interferon-γ and B Cell Stimulatory Factor–1 Reciprocally Regulate Ig Isotype Production

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Gamma interferon (IFN-γ) and B cell stimulatory factor–1 (BSF-1), also known as interleukin-4, are T cell–derived lymphokines that have potent effects on B cell proliferation and differentiation. They are often secreted by distinct T cell clones. It is now shown that IFN-γ stimulates the expression of immunoglobulin (Ig) of the IgG2a isotype and inhibits the production of IgG3, IgG1, IgG2b, and IgE. By contrast, BSF-1 has powerful effects in promoting switching to the expression of IgG1 and IgE but markedly inhibits IgM, IgG3, IgG2a, and IgG2b. These results indicate that BSF-1 and IFN-γ as well as the T cells that produce them may act as reciprocal regulatory agents in the determination of Ig isotype responses. The effects of IFN-γ and BSF-1 on isotype expression are independent.

GAMMA INTERFERON (IFN-γ) promotes the production of immunoglobulin (Ig) by activated murine and human B cells stimulated with interleukin-2 (*1*) and causes human B cells treated with antibodies to Ig to enter the S phase of the cell cycle (*2*). Conversely, IFN-γ inhibits the actions of B cell stimulatory factor–1 (BSF-1) on resting B cells, including BSF-1 induction of class II major histocompatibility complex molecule expression (*3*) and costimulation of proliferation (*4*). IFN-γ also suppresses the enhancement by BSF-1 of IgG1 and IgE synthesis in B cells stimulated with lipopolysaccharide (LPS) (*5*). We show here that IFN-γ induces a selective and striking induction of IgG2a production by resting B cells stimulated with LPS in vitro. Furthermore, both IFN-γ and BSF-1 are potent inhibitors of the expression of specific Ig isotypes; IFN-γ blocks IgG3 and IgG2b (*6*) as well as IgG1 and IgE, whereas BSF-1 blocks IgG3, IgG2b (*7*), IgG2a, and IgM. These results suggest that IFN-γ and BSF-1 reciprocally regulate Ig isotype production in T cell–dependent immune responses and thus determine many of the biologic consequences of such antibody production. Since BSF-1 and IFN-γ appear to be produced by separate sets of T cell clones (*8*), a reciprocal regulatory interaction of T cell subsets may determine Ig isotypic responses to immunization.

Resting B cells were purified from spleens of 8- to 12-week-old DBA/2 mice by incubation with antibodies to Lyt-1, Lyt-2, and Thy 1.2 and complement, followed by Percoll density-gradient centrifugation (*4*). When these cells were stimulated with LPS, they synthesized large amounts of IgM, considerable IgG3 and IgG2b, and small but detectable amounts of IgG1 and IgG2a (*7*). Addition of recombinant IFN-γ (rIFN-γ) (10 U/ml) (*9*) caused a striking increase in IgG2a concentrations and near complete suppression of IgG3, IgG1, and IgG2b production, but had little effect on IgM (Fig. 1). At concentrations of rIFN-γ 30 to 100 times the amount needed to inhibit IgG3, IgG1, and IgG2b completely, suppression of both IgM and IgG2a occurred and could be explained in large part by the striking diminution in viable cell yields at these high rIFN-γ concentrations.

Addition of a hamster monoclonal anti-

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LINKED CITATIONS

References and Notes

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