Summary of Coastal Geologic Evidence for Past Great Earthquakes at the Cascadia Subduction Zone

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Summary of Coastal Geologic Evidence for Past Great Earthquakes at the Cascadia Subduction Zone

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Earthquakes in the past few thousand years have left signs of land-level change, tsunamis, and shaking along the Pacific coast at the Cascadia subduction zone. Sudden lowering of land accounts for many of the buried marsh and forest soils at estuaries between southern British Columbia and northern California. Sand layers on some of these soils imply that tsunamis were triggered by some of the events that lowered the land. Liquefaction features show that inland shaking accompanied sudden coastal subsidence at the Washington-Oregon border about 300 years ago. The combined evidence for subsidence, tsunamis, and shaking shows that earthquakes of magnitude 8 or larger have occurred on the boundary between the overriding North America plate and the downgoing Juan de Fuca and Gorda plates. Intervals between the earthquakes are poorly known because of uncertainties about the number and ages of the earthquakes. Current estimates for individual intervals at specific coastal sites range from a few centuries to about one thousand years.

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INTRODUCTION

Earthquakes of magnitude 8 or larger–great earthquakes–pose a recently discovered hazard to the northwestern United States and southwestern Canada. The earthquakes would occur at the Cascadia subduction zone, an offshore and onshore region over 1,000 km long where several oceanic plates descend eastward beneath the North America plate (Figs. 1, 2). Great earthquakes are not part of the region's documentary history, which begins about A.D. 1790. But as shown in this report, great Cascadia earthquakes have occurred in the past few thousand years, most recently about A.D. 1700.

The purposes of the report are to summarize coastal geologic evidence about the past occurrence of great Cascadia earthquakes, and to present broad ranges of magnitudes and recurrence intervals consistent with this evidence. The report makes only brief mention of other kinds of evidence that bear on Cascadia's great-earthquake potential

The reference list is divided into four sections. The first three sections comprise citations about prehistoric earthquakes at the Cascadia subduction zone: articles in refereed journals and books *(cited with prefix A)*, other reports *(B)*, and abstracts *(C)*. The fourth section lists additional cited reports *(D)*. All these references had been released or were in press by June 1994, when this report was submitted to *Earthquake Spectra.*

SIGNS OF PAST EARTHQUAKES

The main evidence for prehistoric earthquakes at the Cascadia subduction zone consists of coastal strata indicative of sudden lowering of land (sudden subsidence). Some of these strata are associated with evidence for tsunamis, and there is also evidence that seismic shaking accompanied the sudden subsidence.

SUDDEN SUBSIDENCE

Buried marsh or forest soils record sudden subsidence at more than a dozen estuaries between Clayoquot Sound, British Columbia, and the Eel River, California *(A2, A4, A5, A7, A10, A15, A16, A17, A30, A32, A34, A35, B1, B4, B13, B15, B16, B22, B23, C1, C2, C4, C5, C6, C18)* (Figs. 1, 2). Plant fossils and sediment types show that the burial of one or more soils at many of the estuaries resulted from at least ½ m of sudden subsidence. The subsidence allowed tides to deposit mud on land that was previously at or above high-tide level (Fig. 3a). At least at Willapa Bay and the Copalis River, Washington, such subsidence records tectonic lowering of the entire landscape, not just shaking-induced compaction of unconsolidated deposits *(A2, A4).*

There is little geologic evidence for earthquake-induced uplift along the Pacific coast at the Cascadia subduction zone except in northern California, where wave-cut platforms have emerged within the past 10,000 years *(A9, A15, A27, B6, B7, B18, C9, C10, C11).* The most recent uplift accompanied a magnitude-7.1 earthquake on April 25, 1992. This earthquake, which may have occurred at the boundary between the North America and Gorda plates *(A33)*, raised 25 km of the Cape Mendocino coast by as much as 1.5 m *(A9).* Evidence for uplift in the past 10,000 years has also been reported from Cape Blanco, Oregon *(A24)*, from western Vancouver Island *(A14, A19, B14)*, and from Puget Sound *(A8).* But recent work shows that the uplift at Cape Blanco is questionable *(C7)*, and that the uplift on western

Vancouver Island has been punctuated by earthquake-induced subsidence *(A10)*. The uplift at Puget Sound accompanied one or more shallow inland earthquakes that did not necessarily coincide with plate-boundary slip *(A4, A8)*.

Some parts of the Cascadia subduction zone contain thick bodies of tidal-marsh peat that preclude sudden subsidence or uplift greater than ½ m in the past few thousand years. Such peat probably built upward apace with a gradual rise of the sea and (or) a gradual fall of the land. It has been found along the Strait of Georgia and northern Puget Sound *(A18, A25, B2, B8)* and in the seaward part of the Siuslaw River estuary of southern Oregon *(A30, A32, B4)* (Figs. 1, 2). The peat shows that sudden coastal subsidence greater than ½ m extended neither eastward into the Strait of Georgia and northern Puget Sound *(A25, B8)* nor southward, as an uninterrupted belt of coastal subsidence, into southern Oregon. The thick peat along the Siuslaw River may mark a lateral margin of such a subsidence belt *(A35)*, or it may indicate that sudden subsidence in southern Oregon was localized along synclines in the North America plate *(A30, A32)*.

TSUNAMIS

Some of the buried soils indicative of sudden subsidence are covered by sand layers suggestive of tsunamis. Such sand layers have been found beneath coastal lowlands in British Columbia *(A10, A11, A12)*, Washington *(A2, A4, A7, B17, C20, C21)*, and Oregon *(A16, A17, B4, B9, B11, C4, C5, C7)*. Deposition of the sand probably coincided with subsidence of the underlying soil; the sand rests rests directly on the soil and is overlain by intertidal mud. In some cases the sand surrounds growth-position stems and leaves of herbaceous plants that had been living on the soil before it subsided *(A7, A10)*. The preservation of these plant remains implies close coincidence between the event that caused the soil to subside and the surge of water that covered the soil with sand. Such coincidence would be expected of an earthquake that causes a coast to subside while generating a tsunami in the adjacent ocean (Fig. 3b).

SHAKING

Seismic shaking produced liquefaction features less than 3,000 years old near Vancouver, British Columbia *(A13, A25)*; along the Washington-Oregon border at the Columbia River estuary *(B1, B20, C15, C16)*; about 70 km east of Grays Harbor, Washington *(B20, C12)*; and near Portland *(C22)* and Cape Blanco *(C7)*, Oregon. Earthquakes also appear to have produced liquefaction features probably tens of thousands to hundreds of thousands of years old in coastal Washington and Oregon *(C19)*; turbidity-current deposits less than 8,000 years old in deep-sea channels off Washington and Oregon *(A1)*; and enigmatic bodies of intruded and extruded sand about 1,000 years old at the Copalis River, Washington *(A4)*. In addition, prehistoric earthquakes probably triggered landslides and subaqueous mass movements in British Columbia *(B3)*, Washington *(A21, A23)*, and Oregon *(B11)*.

Of the various kinds of evidence for prehistoric shaking at the Cascadia subduction zone, only the liquefaction features along the lower Columbia River provide strong evidence that onshore shaking accompanied sudden land-level change along the Pacific coast. These features, identified 30-60 km inland from the coast, include sand that erupted onto tidal swamps about 300 years ago at or near a time of sudden subsidence (Fig. 3c) *(B1, B20, C15)*.

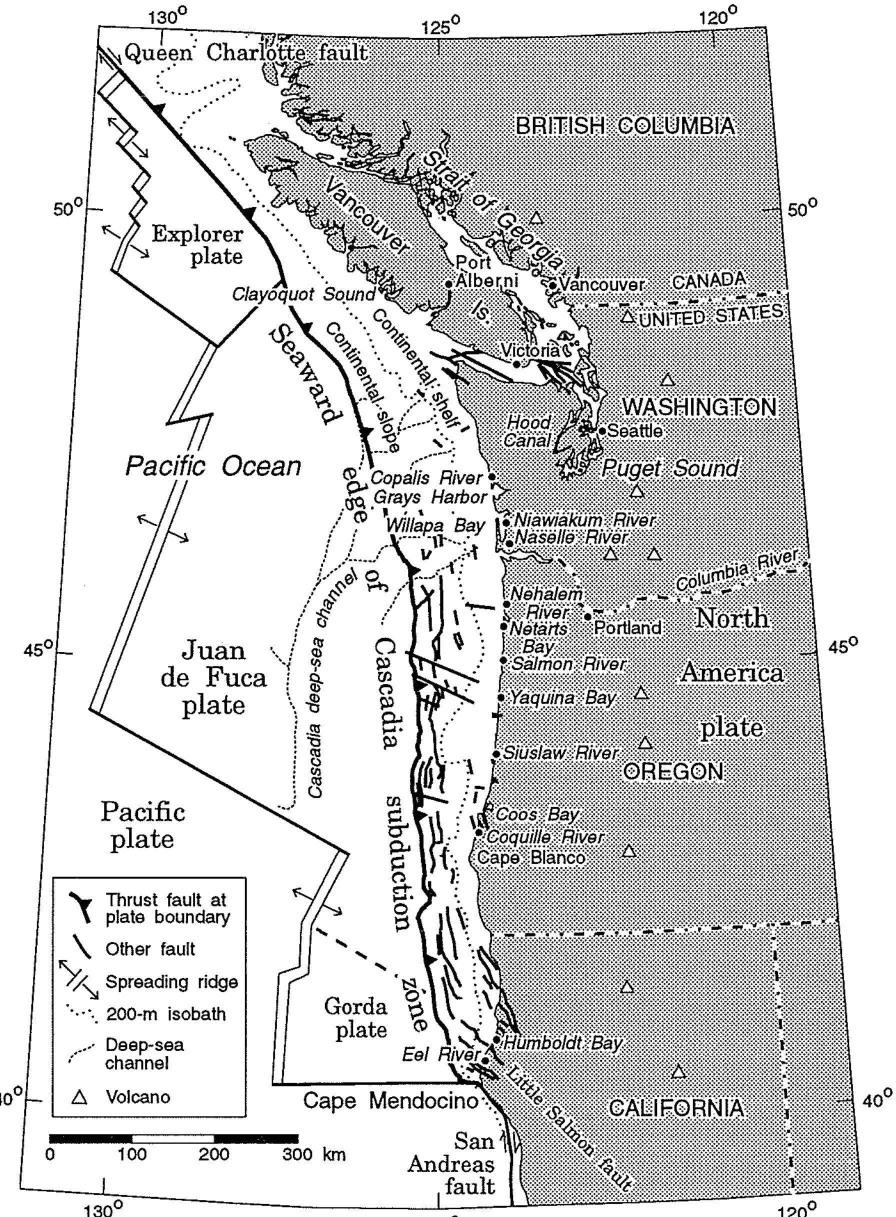

Figure 1 Cascadia subduction zone, showing place names, plate boundaries, and recently active faults within the North America plate. Barbs denote dip of plate-boundary thrust, which extends eastward beneath the coast. Faults shown have been active in the past 2 million years; source map in reference *D18* with modifications from *A15, B12, D21,* and *D22*. Reference *B12* depicts many additional faults of this kind on the continental shelf and slope off Oregon; most of these faults trend approximately parallel to the coast.

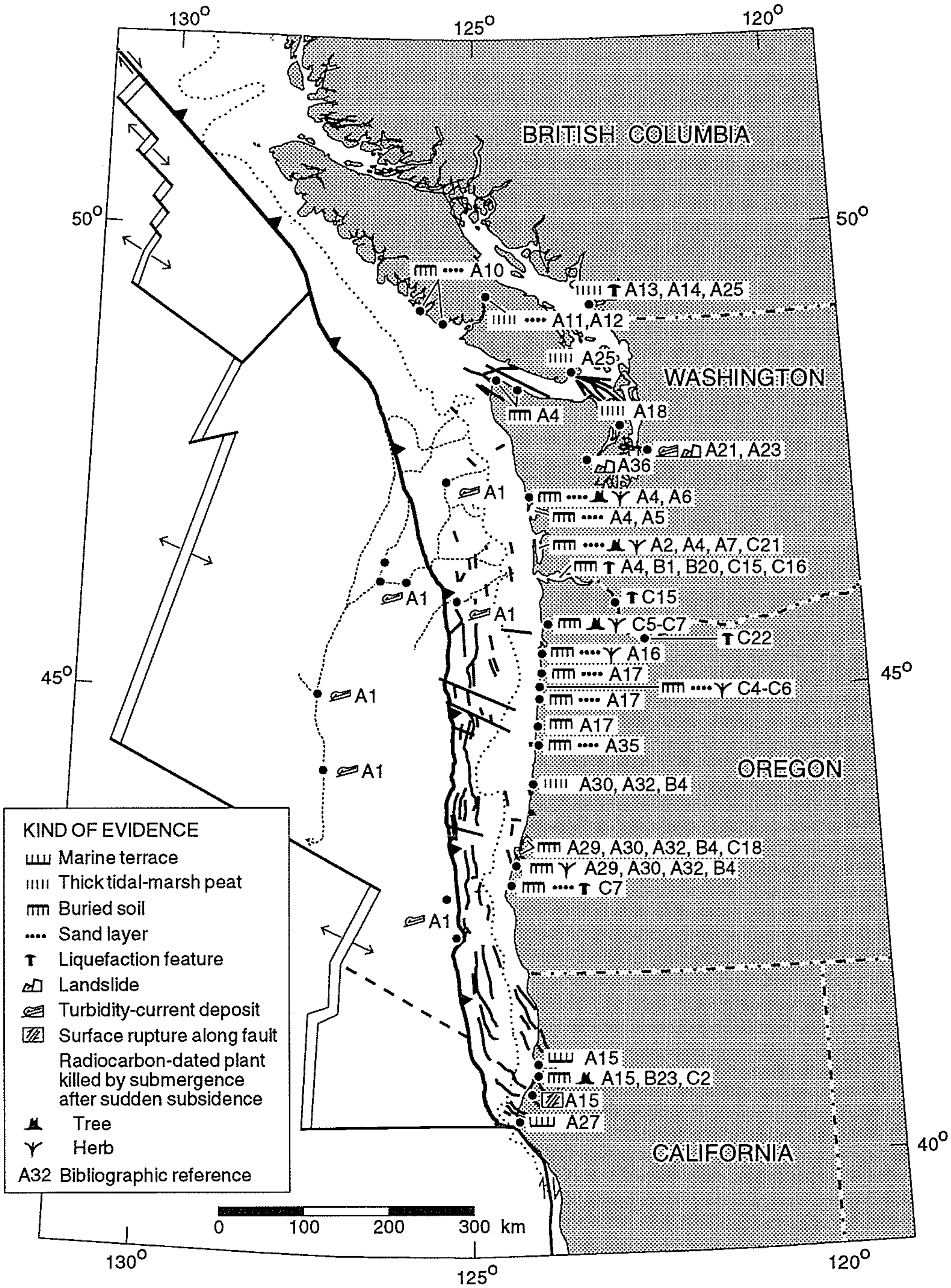

Figure 2 Distribution of principal geologic evidence bearing on prehistoric plate-boundary seismicity at the Cascadia subduction zone. Radiocarbon ages for killed plants are reported in *A6, C2,* and *C14*.

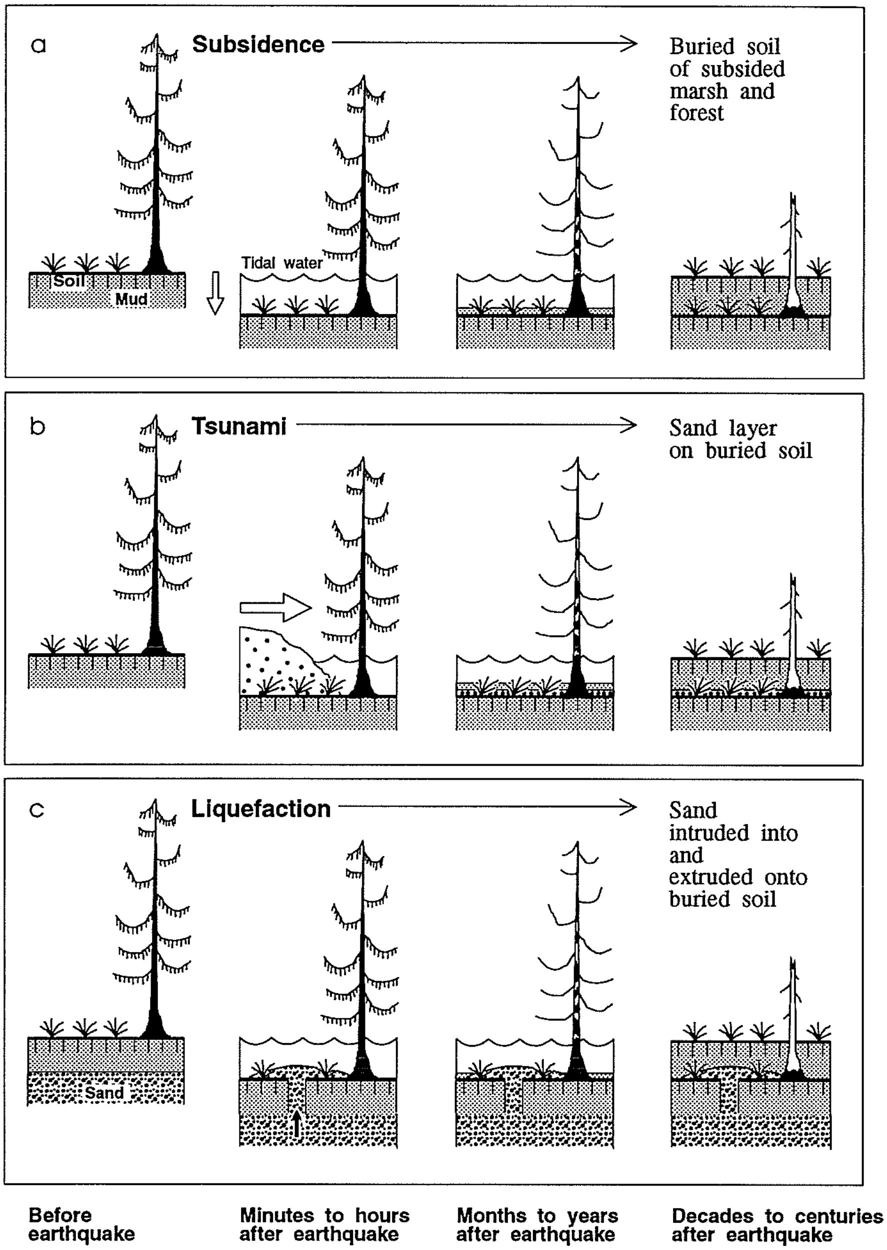

Figure 3 Inferred origin of the main coastal features cited as evidence for prehistoric earthquakes at the Cascadia subduction zone. **(a)** Soil buried by tidal mud after earthquake-induced subsidence lowers land into the intertidal zone. **(b)** Sand sheet deposited on a subsided soil by a tsunami that comes ashore minutes to hours after and earthquake. **(c)** Liquefied sand that erupted through and onto a subsided soil as a result of seismic shaking.

Liquefaction features are rare in gravelly alluvium of southwestern Washington *(B20, C12)*. Little is known about conditions required to produce liquefaction features in this material.

EARTHQUAKE MAGNITUDE

GREAT EARTHQUAKES ON THE PLATE BOUNDARY

The boundary between the North America plate and the Juan de Fuca and Gorda plates is a giant thrust fault with a widely acknowledged but historically unrealized potential for generating earthquakes of magnitude 8 or larger *(D6, D18)*. This potential has been inferred geophysically from comparison with other subduction zones *(D7, D19)* and from geodetic and heat-flow evidence that the Cascadia subduction zone is accumulating energy that could be released in future plate-boundary earthquakes *(D5, D9, D13, D20)*.

Great plate-boundary earthquakes probably account for most, but not necessarily all, of the prehistoric land-level changes, tsunamis, and shaking mentioned above. As shown in the following paragraphs, such earthquakes are compatible with coastal geologic evidence bearing on the location and size of ruptures, potential amounts of seismic displacement, and intensity of inland shaking.

Rupture Location

Rupture at the plate boundary provides a simple explanation for sudden coastal subsidence during the past few thousand years at the Cascadia subduction zone. The plate boundary should have been active during this interval because it accommodates present-day convergence between plates *(D7)*. A plate-boundary rupture could have caused sudden coastal subsidence by elastically thinning the North America plate *(A2, A16, A20)*; such thinning explains the sudden subsidence, during the great 1964 Alaska earthquake, of a largely coastal area 800 km long and 100 km wide in south-central Alaska *(D7, D15)*. Plate-boundary rupture also could have caused localized subsidence along shallow folds and faults in the North America plate *(A15, A20, A26, A30)*; the 1964 earthquake was accompanied by movement on upper-plate structures at the Gulf of Alaska *(D15)*.

Rupture Area

Because a magnitude-8 earthquake ruptures an area of about 10,000 km^2 *(D23)*, a plate-boundary rupture 50 km wide and 200 km long at the Cascadia subduction zone would probably correspond to an earthquake of this size. Likewise, a magnitude-9 Cascadia earthquake would probably entail plate-boundary rupture averaging 100 km wide along the 1,000 km between central Vancouver Island and Cape Mendocino *(D7, D19)*.

Rupture Width. Geophysicists have estimated that seismic ruptures at least 40-100 km wide could occur at the boundary between the Juan de Fuca and North America plates. These estimates are based on geodetic and heat-flow data *(D5, D9, D13, D20)*.

Ruptures tens of kilometers wide are consistent with the extent of sudden subsidence measured perpendicular to the central part of the Cascadia subduction zone. The width of rupture during a great subduction-zone earthquake can resemble the extent of the resulting subsidence measured perpendicular to the subduction zone, as shown by historical earthquakes in Japan *(D1)*, Chile *(D2, D16),* and Alaska *(D15).* At the Cascadia subduction zone, sudden subsidence about 300 years ago extended east-west, perpendicular to the subduction zone, for no less than 35 km at Grays Harbor, 25 km at Willapa Bay, and 30 km at the Columbia River *(A4, B1).* These east-west distances appear limited by the extent of tidal wetlands suitable for recording the subsidence, not by the extent of the subsidence itself.

Ruptures tens of kilometers wide also accord with the scarcity of evidence for earthquake-induced uplift along the Pacific coast of Washington and Oregon. In the 1980s this scarcity, along with modest uplift of marine terraces tens of thousands to hundreds of thousands of years old, led some earth scientists to conclude that great Cascadia earthquakes may not have occurred in the past 10,000 years or more *(A37, A38, C23).* However, modern great earthquakes at some subduction zones have been accompanied by little or no coastal uplift *(A3)* and have occurred in areas of long-term net uplift as slow as at the Cascadia subduction zone *(A28).* No widespread coastal uplift accompanied the great 1960 earthquake in southern Chile, which instead caused sudden subsidence along nearly 1,000 km of Chilean coast above the landward part of a seismic rupture 100-150 km wide *(D2, D16).*

Rupture Length. Geologic dating of prehistoric sudden subsidence provides a direct but imprecise measure of the lengths of past plate-boundary ruptures at the Cascadia subduction zone. Such dating lacks the precision to prove that any single rupture extended along hundreds of kilometers of coast. No geologic dating is likely to discriminate between a magnitude-9 rupture and a series of adjacent, shorter ruptures if the shorter ruptures are as nearly coincident as the pair of magnitude-8.5 earthquakes that occurred 32 hours apart along a Japanese subduction zone in 1854 *(D1).* But the most precise of the dating at the Cascadia subduction zone could *disprove* the occurrence of a long rupture by showing differences in age indicative of short ruptures several decades apart, such as the subduction-zone earthquakes of magnitude 7½-8 off Columbia and Ecuador in 1942 and 1979 *(D11, D12).* Failure to detect such differences has strengthened the great-earthquake intepretation of coastal subsidence that occurred at the Cascadia subduction zone about A.D. 1700.

Geologic dating of the most recent time of widespread sudden subsidence at the Cascadia subduction zone shows that a single rupture, or a brief series of ruptures, extended along hundreds of kilometers of the Pacific coast about A.D. 1700. Such extensive rupture best explains the timing of tree death in forests killed by tidal submergence soon after sudden subsidence (Fig. 3a) at the Copalis River and Willapa Bay, Washington; the Nehalem River, Oregon; and Humboldt Bay, California (Figs. 1, 2). High-precision radiocarbon dating of these subsidence-killed trees shows that the most recent sudden subsidence at Willapa and Humboldt Bays, and probably also at the Copalis and Nehalem Rivers, occurred between A.D. 1680 and 1720 *(A6, C2, C14).* Less-precise radiocarbon dating of herbaceous plants killed soon after subsidence (Fig. 3a) shows that the most recent subsidence postdates A.D. 1650 at the six estuaries where such plants have been dated (Figs. 1, 2): the Copalis River and Willapa Bay, Washington; and Netarts Bay, and the Nehalem, Salmon, and Coquille Rivers, Oregon *(C14).* The most recent subsidence has also been dated to the late 1600s or early 1700s by matching of ring-width patterns in subsidence-killed trees at Grays Harbor, Willapa Bay, and the Copalis and Columbia Rivers, Washington *(C24).*

Numerical ages have provided little basis for estimating rupture lengths during earlier times of sudden subsidence at the Cascadia subduction zone. In most cases the ages have geologic and analytical uncertainties that could obscure differences as large as several hundred years.

Rupture lengths at the Cascadia subduction zone have been estimated indirectly through comparison with other subduction zones and speculation about rupture-limiting segmentation. Reliance on such evidence led to a recent proposal that maximum rupture length at the Cascadia subduction zone is probably close to 250 or 450 km *(D6).*

Seismic Slip

Intervals between the geologically recorded earthquakes imply the release of many meters of accumulated strain. The intervals estimated from coastal geology are mainly on the order of centuries (see "Earthquake Recurrence" below), and about three centuries have elapsed since the most recent of the great earthquakes. With convergence at the Cascadia subduction zone averaging about 4 m per century *(D17)*, three centuries of convergence yields more than 10 m of potential seismic slip, five centuries about 20 m. By comparison, slip during the 1960 Chile and 1964 Alaska earthquakes averaged about 20 m *(D2, D15, D16).*

Although recurrence intervals measured in centuries thus imply large amounts of seismic slip, the actual seismic slip at the Cascadia subduction zone should be smaller than the product of convergence rate and recurrence interval. Part of the plate convergence at the Cascadia subduction zone is probably consumed by permanent deformation within the North America plate (*A20*), and part might be accommodated by aseismic slip at the plate boundary *(D10, D14).*

Inland Shaking

Seismologists have estimated levels of ground motion that could result from great Cascadia earthquakes. The estimates depend on analogy with historical earthquakes at other subduction zones and on speculation about rupture location, rupture dimensions, and ground-motion attenuation at the Cascadia subduction zone *(D3, D4, D8, D24).*

The estimated ground motions have been tentatively compared with geologic evidence for and against prehistoric shaking along the lower Columbia River. This evidence was found consistent with ground motion from an offshore plate-boundary earthquake no smaller than magnitude 7 *(B10, B20, C16).* Magnitude 7 is a lower bound because liquefaction along the lower Columbia River may have occurred in denser sand *(B1)* and may have extended farther inland *(C22)* than was assumed in the comparisons.

EARTHQUAKES ON FAULTS IN THE NORTH AMERICA PLATE

Earthquakes of magnitude 7 on faults within the North America plate provide an alternative explanation for some of the prehistoric land-level change in northern California *(A15).* There, nearshore and onshore faults have slipped within the past 10,000 years, and coastal land has subsided suddenly within the past few thousand years along synclines that approximately parallel youthful faults. Moreover, sudden subsidence along a syncline at Humboldt Bay occurred within the same few-century interval as did surface-rupturing earthquakes on the nearby Little Salmon fault, on three different occasions in the past 2,000 years *(A15, B5, B6, B7, B23).* If the Little Salmon fault broke along its entire 100-km length, most of which is offshore (Fig. 1), the rupture area could have been about 1,000 km^2 (*A15*).

Correlations between earthquake magnitude and rupture area *(D23)* suggest that such an earthquake would have had an approximate magnitude of 7.

Earthquakes from the North America plate may also explain some of the sudden subsidence farther north. The North America plate off the Pacific coast of Oregon and Washington contains shallow faults on which slip has occurred during the past 10,000 years *(A20, B12, C3, C8, C25)*. Several of the Oregon estuaries with evidence for sudden subsidence are located along the eastward projection of such offshore structures *(A20, C8)*. In addition, sudden subsidence during the past few thousand years at Yaquina and Coos Bays, Oregon *(A17, A30, A32, B4, C1, C18)* has occurred along synclines near and parallel to faults that have probably slipped within the past 100,000 years *(A26 , B21)*. As noted above, localization of subsidence along these synclines is among possible explanations for the thick tidal-marsh peat at the intervening Siuslaw River *(A30, A32)*.

EARTHQUAKE RECURRENCE

Intervals of hundreds of years and, possibly, more than a thousand years, have separated successive earthquakes at specific sites along the Cascadia subduction zone *(A4, A5, A15, A16, A30, A32, A34, B11, B19, B22, B23, C4)*. The estimated intervals are imprecise because of two kinds of problems:

(1) *The number of earthquakes recorded geologically may differ from the number that actually occurred.* An overestimate could result where some buried soils record non-seismic events, such as breaching of tide-restricting bars, changes in tidal-inlet shape, changes in sediment supply, or rapid sea-level rise *(A30, A32, C13)*. Such origins for buried soils may complicate the earthquake-recurrence record at many of the estuaries; they need evaluation through detailed studies of sediments and fossils *(A22, A25, A31, B13, C13)*. An underestimate could result where a buried soil has disappeared through oxidation *(A4, A5)* or erosion *(A30)*, or where a soil escaped burial through lack of tidal submergence *(A4)* or sediment supply *(A30, A32)*.

(2) *Errors in dating can approach or exceed the lengths of time between the inferred earthquakes.* The total uncertainty in the age assigned to an earthquake can include errors in radiocarbon analysis, errors in converting radiocarbon age to calendric age, and errors in estimating the difference between the age of an analyzed sample and the time of the earthquake. At the Cascadia subduction zone the sum of such errors commonly amounts to hundreds of years *(A4, A11, A29)*.

Such problems with the counting and dating of prehistoric earthquakes cast doubt on reported geologic estimates of average recurrence intervals for great Cascadia earthquakes. The reported estimates, which are between 400 and 600 years *(A1, C17, D6)*, have unstated uncertainties that may total many hundreds of years.

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