chanical model for a throughgoing fault may be possible after event relocation analysis. Relocated events may reveal en echelon strike-slip movement in agreement with wrench-zone models or tabular zones striking parallel to the northwest boundary of the Ocoee block, suggesting general weakening of the crust leading to possible failure.

Our model for seismicity in the ETSZ has implications for seismic hazard assessment. If a throughgoing fault is developing along the northwest boundary of the Ocoee block, the potential for a future large earthquake may be higher than the historical record suggests. However, the estimation of when a potentially damaging event may occur is speculative.

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Detection of Large Prehistoric Earthquakes in the Pacific Northwest by Microfossil Analysis

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Geologic and palynological evidence for rapid sea level change ~3400 and ~2000 carbon-14 years ago (3600 and 1900 calendar years ago) has been found at sites up to 110 kilometers apart in southwestern British Columbia. Submergence on southern Vancouver Island and slight emergence on the mainland during the older event are consistent with a great (magnitude $M \geq 8$) earthquake on the Cascadia subduction zone. The younger event is characterized by submergence throughout the region and may also record a plate-boundary earthquake or a very large crustal or intraplate earthquake. Microfossil analysis can detect small amounts of coseismic uplift and subsidence that leave little or no lithostratigraphic signature.

There is mounting concern that coastal areas of the Pacific Northwest of the United States and Canada could experience an earthquake much larger than any of the historical period (*1*). Geodetic data and geophysical modeling (*2, 3*) indicate that converging plates within the Cascadia subduction zone (Fig. 1) are locked and accumulating strain, portending a great ($M \geq 8$) plate-boundary earthquake in the future.

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There is also compelling geologic evidence for large prehistoric earthquakes, both on the Cascadia subduction zone (*4, 5*) and at relatively shallow depth within the North American plate (*6*).

Geophysical models (*3*) and crustal deformation patterns of historical plate-boundary earthquakes in Alaska and Chile (*7*) suggest that part of the Pacific coast between northern California and central Vancouver Island would subside during an earthquake on the Cascadia subduction zone. The amount of subsidence would decrease eastward, approaching zero several tens of kilometers east of the outer coast. A large earthquake within the North American or Juan de Fuca plate might also cause uplift or subsidence, although the affected area probably would be smaller.

We present evidence for two large earthquakes that affected sites in south-coastal British Columbia up to 110 km apart. Much of the evidence comes from an analysis of fossil pollen, spores, and other microfossils in Holocene peat deposits. Small amounts of emergence and submergence, even with little or no lithologic expression, can be detected from such records.

The study area includes southern Vancouver Island and the British Columbia mainland in the vicinity of the Fraser and Serpentine rivers (Fig. 1). Peaty wetlands at or near the upper limit of tides were selected for study because plants growing there are strongly influenced by small differences in elevation and salinity (*8*) and are thus potentially sensitive indicators of coseismic subsidence or uplift. Subsidence might transform freshwater shrublands or marshes into tidal marshes, whereas uplift might convert herbaceous, salt-tolerant plant communities into supratidal vegetation.

Holocene vegetation changes in Fraser delta wetlands have previously been attributed to natural succession or river flooding (*9*). While these processes are undeniably important, our results indicate that earthquakes may be implicated in at least two instances of rapid vegetation change at ~3400 and ~2000 ^{14}C years B.P. (radiocarbon years before present, taken as A.D. 1950; 3600 and 1900 calendar years ago).

These events are most clearly recorded on the coast of southern Vancouver Island and along the Serpentine River, south of Vancouver. Rooted stumps, logs, branches, cones, and peaty forest soil are exposed at low tide at the mouth of Muir Creek (Fig. 1). Nearby, the fossil forest is abruptly overlain by silt and sand containing brackish water diatoms. Wood from the peat bed has been dated at 3280 ± 50 and 3530 ± 60 ^{14}C years B.P., suggesting that the forest was submerged and killed at about that time (Table 1). Farther east, at Island View Beach, in situ fossil stumps 1.0 to 1.5 m below the upper limit of tides indicate another transgression. One of the stumps yielded a radiocarbon age of 2040 ± 130 ^{14}C years B.P. Finally, numerous stumps are exposed in the banks of the Serpentine River about 1 m below high tide level. The stumps are rooted near the top of a widespread peat that is abruptly overlain by intertidal mud. A radiocarbon age of 2290 ± 60 ^{14}C years B.P. on one of the stumps is a maximum for submergence and mud deposition.

On the basis of these observations alone, it is not possible to determine whether the transgressions at Muir Creek, Island View Beach, and Serpentine River were the result of subsidence during earthquakes, aseismic subsidence, or eustatic sea level rise

(10). They must have been rapid enough, however, to preserve remnants of the transgressed forests. The inference that these events are linked to large earthquakes is based on the stratigraphy, paleoecology, and chronology of late Holocene sediment sequences at these and other sites.

Site stratigraphy was determined from vibracores (Gyro Park), piston cores (Colebrook Road and Burns Bog), a backhoe trench (Casa Oliveira), and riverbank exposures (Serpentine Fen). At each site, we collected samples for analysis of pollen, foraminifera, and diatoms and for radiocarbon dating. Samples of wood, charcoal, seeds, or peat were selected for dating after microfossil analyses were completed. The dated samples were from levels marked by abrupt changes in stratigraphy or microfossil composition (Fig. 2 and Table 1). These changes typically occur between samples 5 cm or less apart.

Most of the study sites have continuous sequences of sediments spanning the last 4000 to 5000 years. Rapid changes in nearshore vegetation occurred throughout the region on two occasions during this period, namely at ~3400 and ~2000 ^{14}C years B.P. (events 1 and 2, Fig. 3). These two events are marked by pronounced lithologic changes at some sites, whereas at others (for example, Colebrook Road), they have no discernible lithostratigraphic signature.

At the event 1 boundary in the Colebrook Road core (3450 ± 60 ^{14}C years B.P.), a local herb wetland dominated by sedge (Cyperaceae) was rapidly replaced by a shrubland community with abundant sweet gale (*Myrica gale*) (Fig. 3). Although *Myrica* can grow at the extreme upper limit of tides (11), it is more common at slightly higher elevations and is an important pioneering shrub in seismically uplifted wetlands in coastal Alaska (12). The sudden establishment of a *Myrica* shrubland at Colebrook Road thus suggests that the site became slightly higher and drier, which is consistent with uplift.

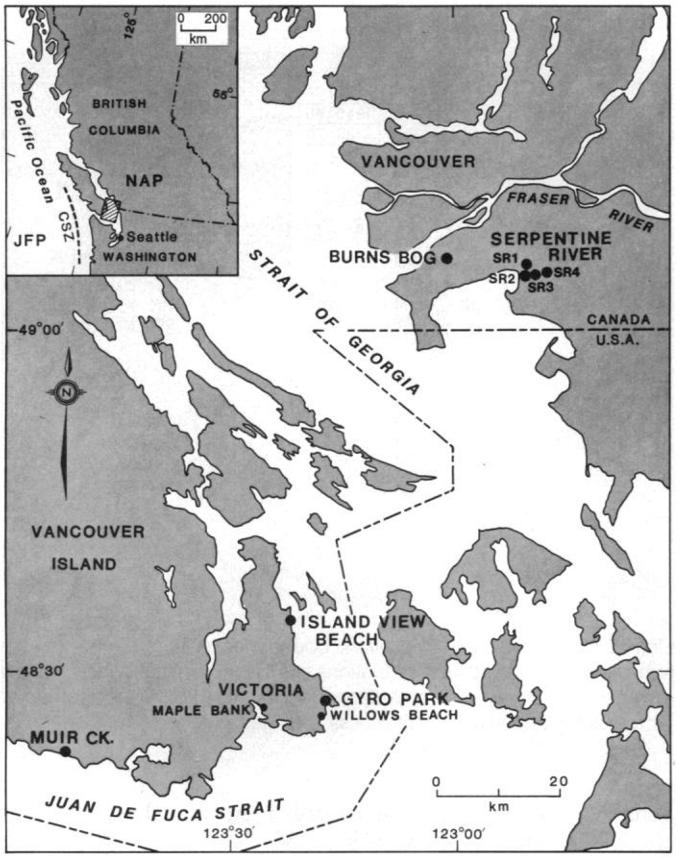

Fig. 1. Location map showing study sites. The dashed line on the inset is the Cascadia subduction zone (CSZ) where the Juan de Fuca plate (JFP) is subducting beneath the North American plate (NAP), creating the potential for large earthquakes.

Table 1. Radiocarbon ages.

Site	Age*		Lab. no.†	Dated material‡	Comment (inference)
	^{14}C years B.P.	Calendar years B.P.			
				Event 1	
Muir Creek	3280 ± 50	3420 to 3570	GSC-5610	Log	Top of forest bed (subsidence)
Muir Creek	3530 ± 60	3700 to 3880	GSC-4758	Log	Top of forest bed (subsidence)
Gyro Park	3380 ± 60	3470 to 3820	TO-2630	Wood fragment	Increase in brackish microfossils (marine incursion, subsidence)
Serpentine Fen	3490 ± 50	3630 to 3880	TO-2133	*Scirpus* seeds	Change from lagoonal sediments to freshwater peat (uplift)
Colebrook Road	3450 ± 60	3560 to 3850	TO-2118	*Scirpus* seeds	Many microfossil changes (Fig. 2) (marine incursion, uplift)
Burns Bog	3740 ± 170	3630 to 4540	S-3190	Peat	Sharp decline in brackish pollen and diatoms, increase in freshwater microfossils (uplift)
				Event 2	
Island View Beach	2040 ± 130	1830 to 2140	GSC-252	Rooted stump	Stumps and freshwater peat in intertidal zone (subsidence)
Gyro Park	1960 ± 70	1820 to 1980	GSC-4902	Peat	Minor microfossil changes, start of silt deposition (subsidence)
Gyro Park	2000 ± 60	1820 to 2110	TO-2628	Charcoal	Increase in brackish pollen and diatoms (subsidence)
Casa Oliveira	1930 ± 100	1610 to 2120	S-3185	Peat	2-cm muddy peat bed, decline in *Myrica*, presence of brackish microfossils (marine incursion, subsidence)
Serpentine Fen	1940 ± 80	1810 to 1950	GSC-5254	Wood fragment	Shift from shrubland to tidal marsh (subsidence)
Serpentine Fen	2120 ± 70	1990 to 2150	GSC-5179	Log	Shift from shrubland to tidal marsh (subsidence)
Serpentine Fen	2290 ± 60	2140 to 2360	TO-4057	Rooted stump	Stump near top of peat, maximum age for shift from shrubland to tidal marsh (subsidence)
Colebrook Road	1920 ± 60	1710 to 1990	TO-2631	Wood fragment	Sudden microfossil changes (Fig. 2)

*Error terms are 2σ for GSC ^{14}C ages and 1σ for all others. The ^{14}C and calibrated ages are expressed in years before 1950 A.D. Calibrated ages were calculated with CALIB 3.0.3 (16); the range represents the 95% confidence interval based on the 1σ error limits of the ^{14}C age (error multiplier, 1). †Laboratories: GSC, Geological Survey of Canada; S, Saskatchewan Research Council; and TO, IsoTrace (University of Toronto). ‡All ^{14}C ages except TO-4057 are closely limiting maximum ages for submergence or emergence. The outer rings of stumps were dated.

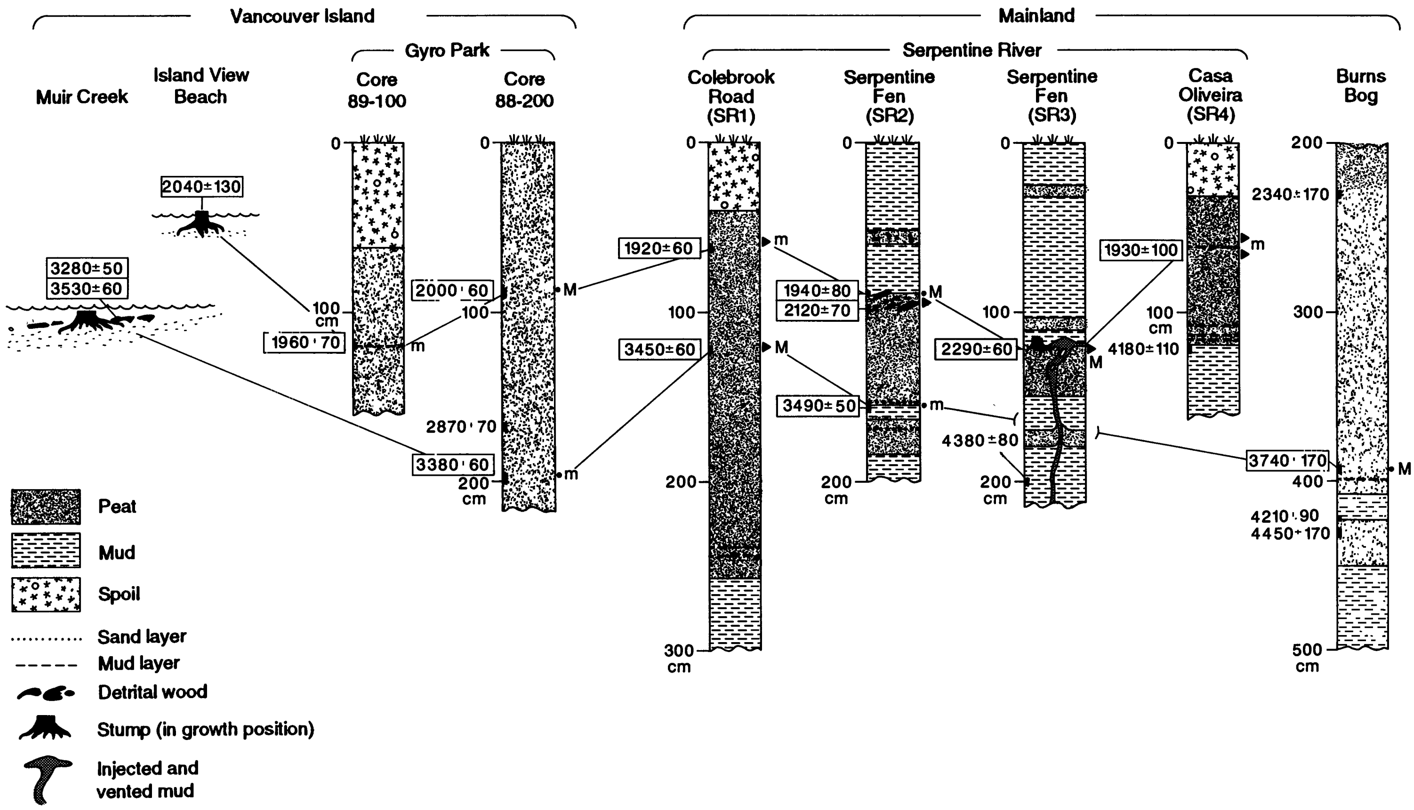

Fig. 2. Stratigraphic sections and correlations of two inferred earthquakes ~3400 and ~2000 ^{14}C years ago. The left side of each section is labeled with the depth (in centimeters) and the radiocarbon age (in ^{14}C years before present). Symbols on the right side indicate microfossil changes at the event boundaries (• M, strong; • m, weak) and *Myrica* peaks (▶). Correlations are based on radiocarbon ages in boxes (at or near event boundary, see Table 1 for details; other ages are supplemental) and microfossil changes. See Fig. 1 for locations of study sites.

The disappearance of foraminifera after event 1 (Fig. 3) supports this inference. Before ~3400 ^{14}C years B.P., foraminifera were deposited episodically in the freshwater marsh at Colebrook Road. A final incursion of brackish water is recorded by tests of the intertidal foraminiferan *Trochammina inflata*, marine diatoms, a small increase in seaside arrow grass (*Triglochin*-type) pollen, and Malvaceae pollen identical to the upper tidal marsh species *Sidalcea hendersonii*. The incursion of brackish water coincides with the inferred uplift and may have been produced by a seismically generated wave that washed inland and left traces of intertidal biota.

Emergence at Colebrook Road was followed by a period of gradual subsidence, indicated by a decrease in *Myrica* pollen and increases in pollen of wetland taxa such as cattail (*Typha latifolia*) and spores of the aquatic algae *Sigmopollis* and *Spirogyra* (Fig. 3).

A similar sequence of events is evident at nearby Burns Bog and Serpentine Fen. At Burns Bog, a fossil assemblage with classical salinity indicators (*Ruppia maritima*, Chenopodiaceae, foraminifera) was suddenly replaced by a freshwater community around 3740 ± 170 ^{14}C years B.P. (Fig. 2 and Table 1). At Serpentine Fen, a brackish aquatic (lagoonal?) sediment containing *Ruppia* seeds and spines of stickleback fish (*Gasterosteus*) is abruptly overlain by freshwater marsh peat; the change occurred about 3490 ± 50 ^{14}C years B.P.

Event 1 on southern Vancouver Island is characterized by minor submergence, indicated by the drowned forest at Muir Creek and by paleoecological data from a former marsh at Gyro Park in Victoria. A shift to wetter and more brackish conditions at Gyro Park about 3380 ± 60 ^{14}C years B.P. is suggested by increases in cattail pollen (from 3 to 25%) and *Sigmopollis* spores (1 to 43%) and the presence of brackish water diatoms.

The pattern of submergence on southern Vancouver Island and minor emergence on the mainland to the east fits the expectation of coseismic deformation caused by a subduction zone earthquake (*7*, *13*). There is geologic evidence from the coasts of southern Washington and northern Oregon for an earthquake on the Cascadia subduction zone at about the same time (*14*).

Rapid vegetation changes marking event 2 are evident at all study sites. At each locality except Colebrook Road, there is a shift to more brackish conditions, indicative of minor submergence ~2000 ^{14}C years ago. Colebrook Road is the highest of the Serpentine River sites and may not have responded to subsidence in the same fashion as the other localities.

Event 2 is particularly well recorded in several exposures along the Serpentine River where a woody terrestrial peat is abruptly overlain by intertidal mud. The contact between the peat and overlying mud coincides with a sharp decline in *Myrica* pollen and corresponding increases in pollen of Chenopodiaceae, Malvaceae, and other brackish indicators.

The in situ stump dated at 2290 ± 60 ^{14}C years B.P. came from one of the Serpentine River exposures. Submergence is more precisely dated at a nearby site where a piece of wood at the top of the peat yielded an age of 1940 ± 80 ^{14}C years B.P. and a log slightly lower in the section dated 2120 ± 70 ^{14}C years B.P. (Fig. 2).

At Serpentine River site SR3, submergence can be directly linked to liquefaction. Dikes of silty mud containing upward-displaced peat clasts cut the lower part of the exposed section. The dikes broaden upward and are continuous with an eroded mound of erupted mud that mantles the peat and is draped by intertidal mud. The stratigraphic relations show that liquefaction occurred at the same time as submergence, suggesting that both phenomena are the result of a large earthquake.

At Casa Oliveira, the farthest inland of the Serpentine River sites, event 2 is

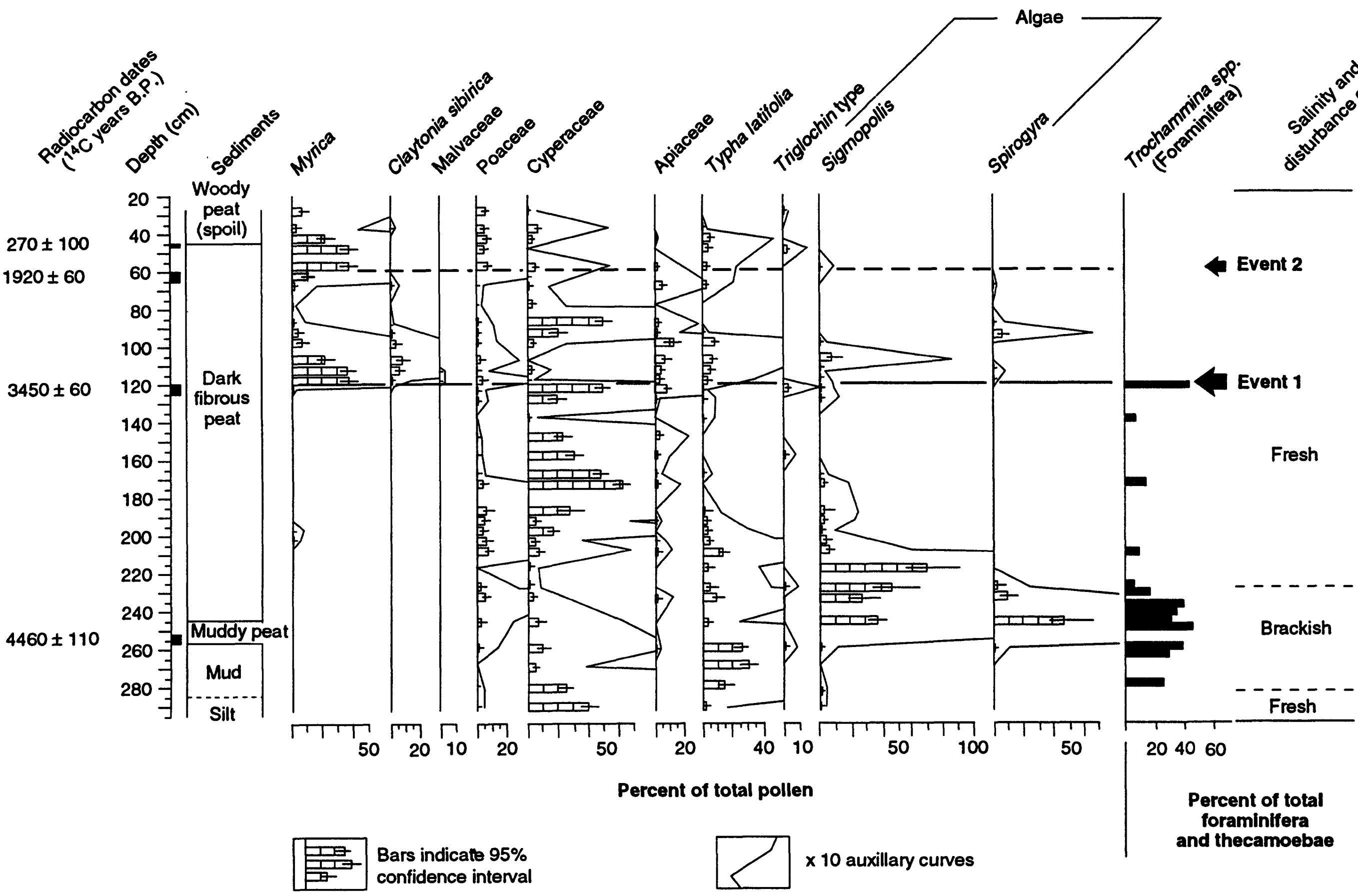

Fig. 3. Microfossil diagram for the Colebrook Road study site (SR1, Fig. 1), showing relative frequencies of selected fossil pollen, spores, and foraminifera. Two periods of rapid vegetation change, delimited by samples spaced 5 cm apart, are labeled events 1 and 2.

marked by a 2-cm-thick layer of muddy peat dated at 1930 ± 100 ^{14}C years B.P. There is a sharp drop in *Myrica* pollen in the muddy peat layer, which suggests that the local shrubland was briefly replaced by herbaceous vegetation, probably as a result of submergence.

There is also evidence for submergence on southern Vancouver Island during event 2. At Island View Beach, mud containing intertidal diatoms sharply overlies freshwater peat at the same stratigraphic level as the 2000-year-old, in situ stumps (*10*). The presence of mud laminae and increases in brackish pollen and diatoms at Gyro Park are also consistent with subsidence ~2000 ^{14}C years ago. Finally, the archaeological record of some coastal sites on southern Vancouver Island provides support for a large earthquake, accompanied by subsidence, at this time (*15*).

The inferred pattern of deformation of the younger earthquake is different from that of the older event. The entire study area seems to have subsided ~2000 ^{14}C years ago, whereas the eastern part of the area may have been uplifted a small amount during the older earthquake ~3400 ^{14}C years ago. The younger earthquake may correlate with a subduction event of about the same age recognized on the southern Washington coast (*5*), or it may have been centered within the North American or Juan de Fuca plate.

The value of using a combined stratigraphic and paleoecological approach in work of this type is clear, and we conclude that the goal of reconstructing earthquake histories in coastal areas can best be achieved by using such integrated studies.

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