Age and significance of earthquake-induced liquefaction near Vancouver, British Columbia, Canada[1]

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Abstract: In late 1994, sand dykes, large sand blows, and deformed strata were exposed in the walls of an excavation at Annacis Island on the Fraser River delta near Vancouver, British Columbia. The features record liquefaction during a large earthquake about 1700 years ago; this was perhaps the largest earthquake to affect the Vancouver area in the last 3500 years. Similar, less well-dated features have been reported from several other sites on the Fraser delta and may be products of the same earthquake. Three radiocarbon ages that closely delimit the time of liquefaction on Annacis Island are similar to the most precise radiocarbon ages on coseismically subsided marsh soils at estuaries in southern Washington and Oregon. Both the liquefaction and the subsidence may have been produced by a single great plate-boundary earthquake at the Cascadia subduction zone. Alternatively, liquefaction at Annacis Island may have been caused by a large crustal or subcrustal earthquake of about the same age as a plate-boundary earthquake farther west. The data from Annacis Island and other sites on the Fraser delta suggest that earthquakes capable of producing extensive liquefaction in this area are rare events. Further, liquefaction analysis using historical seismicity suggests that current assessment procedures may overestimate liquefaction risk.

Key words: liquefaction, earthquake, risk assessment, British Columbia.

Résumé : À la fin de 1994, des digues de sable, de grandes extrusions de sable, et des strates déformées ont été exposéees dans les parois d'une excavation à Annacis Island dans le delta du fleuve Fraser près de Vancouver, Colombie Britannique. Ces singularités font état d'une liquéfaction qui s'est produite au cours d'un grand tremblement de terre datant d'environ 1700 ans; c'était probablement le plus important séisme à avoir affecté la région de Vancouver au cours des derniers 3500 ans. L'on a fait état de singularités semblables mais moins bien datées sur plusieurs autres sites du delta du Fraser et qui pourraient avoir résulté du même séisme. Trois datations au radiocarbone qui délimitent avec un faible écart l'âge de la liquéfaction sur Annacis Island donnent des âges similaires aux datations au radiocarbone les plus précises obtenues sur les sols de marais qui se sont affaissés lors du même séisme dans les estuaires du sud de Washington et de l'Oregon. Tant la liquéfaction que la subsidence peuvent s'être produites au cours d'un seul séisme à la frontière des grandes plaques dans la zone de subsidence de Cascadia. L'alternative étant que la liquéfaction à Annacis Island peut avoir été causée par un séisme important au niveau de la croûte ou sous la croûte terrestre ayant le même âge environ que le séisme à la frontière des plaques plus à l'ouest. Les données de Annacis Island et des autres sites dans le delta du Fraser suggèrent que des séismes capables de produire une liquéfaction étendue dans cette zone sont des évènements rares. De plus, l'analyse de la liquéfaction au moyen de données historiques de séismicité suggère que les procédures actuelles d'évaluation peuvent surestimer le risque de liquéfaction.

Mots clés : liquéfaction, tremblement de terre, évaluation du risque, Colombie Britannique.
[Traduit par la rédaction]

Introduction

Great earthquakes (magnitude 8 or larger) occur at intervals ranging from a few centuries, or less, to nearly a thousand years at the Cascadia subduction zone in the northwestern United States and southwestern Canada (Fig. 1; Atwater et al. 1995; Darienzo and Peterson 1995; Atwater and Hemphill-Haley 1996). There is abundant coastal geological evidence for many great subduction, or plate-boundary, earthquakes in late Holocene time, the most recent about AD 1700 (Nelson et al. 1995; Satake et al. 1996). The earthquakes have left signs of sudden land-level change, tsunamis, and shaking along the outer coasts of British Columbia, Washington, Oregon, and northern California (Atwater et al. 1995; Darienzo and Peterson 1995; Atwater and Hemphill-Haley 1996; Nelson et al. 1996*a*, 1996*b*).[2]

Large earthquakes in the upper part of the North America plate have left similar geological signs (Bucknam et al. 1992; Clarke and Carver 1992). At other subduction zones, such earthquakes have occurred both independently of and concurrently with plate-boundary earthquakes. Uncertainty about the source of some large prehistoric earthquakes along the Cascadia margin (Atwater 1992; Bucknam et al. 1992; Clague

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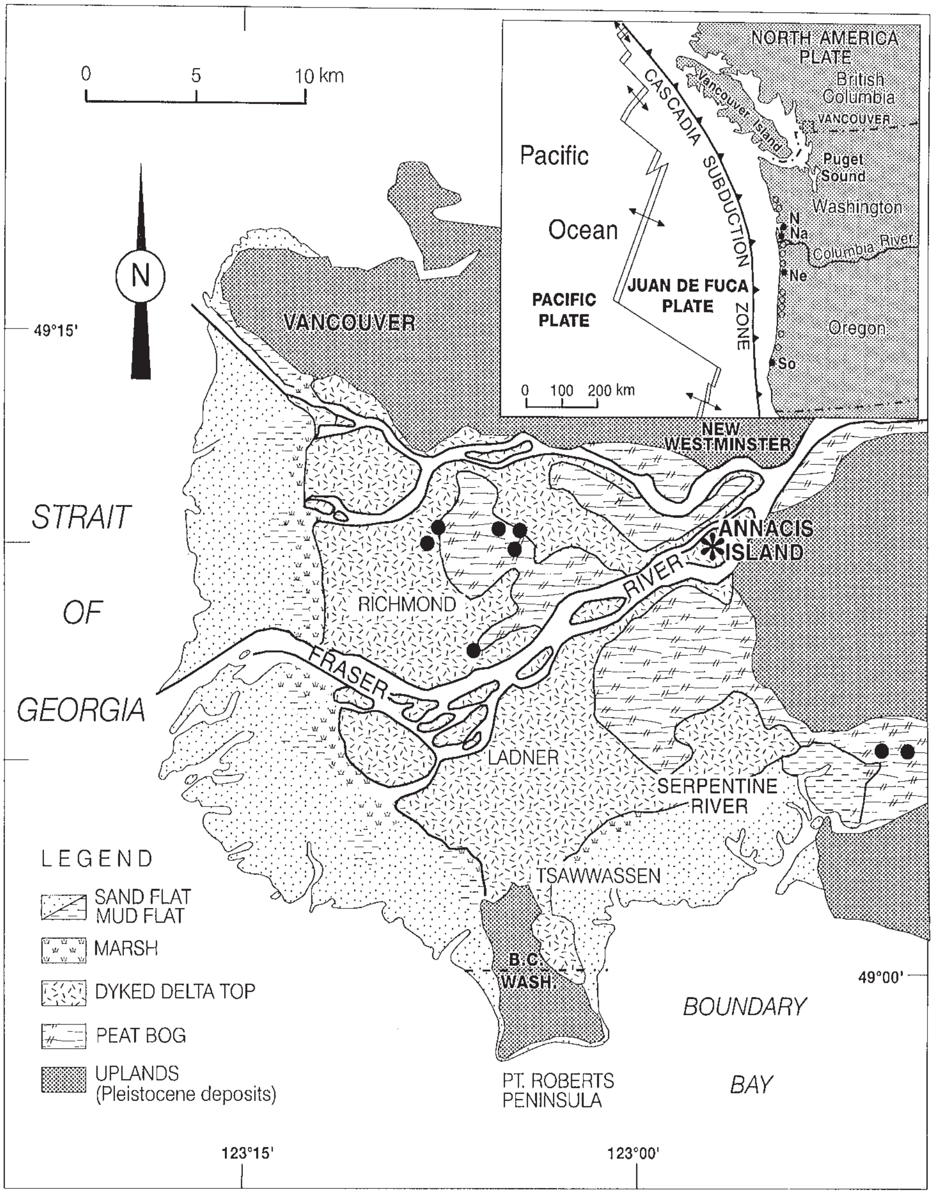
[1] Geological Survey of Canada Contribution 1996118.

[2] Papers and other reports on Cascadia plate-boundary earthquakes published prior to 1995 are listed in Atwater et al. (1995).

Fig. 1. Map of the Fraser River delta and surrounding area, showing locations of sites where late Holocene sand dykes and sand blows have been found (Clague et al. 1992); the Annacis Island site is starred. Inset map shows estuaries in Washington and Oregon where there is evidence of sudden coastal subsidence 1500–1700 years ago. Solid dots locate four sites where this event has been most precisely dated (N, Niawiakum River, Willapa Bay; Na, Naselle River, Willapa Bay; Ne, Netarts Bay; So, South Slough, Coos Bay); open dots locate other sites with less precise ages.



et al. 1992; Nelson 1992; Mathewes and Clague 1994) hampers the assessment of seismic hazard and risk at Vancouver, Seattle, Portland, and other cities in the region.

In this paper, we describe liquefaction features on the Fraser River delta near Vancouver, British Columbia, that are inferred to have been produced by strong ground shaking during an earthquake. The earthquake occurred at about the same time as a great Cascadia plate-boundary earthquake, which is recorded in sediments at several localities on the Pacific coast of southern Washington and Oregon. The two earthquakes could be the same event or, alternatively, could be separate earthquakes of about the same age. We argue, although not conclusively, that ground shaking strong enough to produce widespread liquefaction on the Fraser delta occurs very infrequently.

Setting

The Fraser River delta plain extends 15–23 km west and south into the Strait of Georgia from a narrow gap in Pleistocene uplands at New Westminster (Fig. 1). The subaerial inhabited portion of the delta is protected by levees and is 1–4 m above mean sea level, with the water table within 2 m of the surface. Very gently sloping tidal flats and the fringing subtidal part of the delta plain extend up to 9 km from the dyked edge of the delta.

Fig. 2. Top: map of the Annacis Island sewerage treatment facility and surrounding area, showing the locations of studied liquefaction features and auger and cone-penetrometer test holes. Bottom: seismic cone-penetrometer (SCPT) logs, grain-size data for samples recovered from an auger hole, and interpreted lithologies (organic soil below sand fill shown as thin grey band). Qt, cone-tip bearing pressure; R_f, cone friction ratio; U, pore pressure behind the cone tip; V_s, shear-wave velocity; fines, percent < 0.075 mm; D_{50}, median diameter. The low water level at the time of drilling resulted from pumping at the construction site. 1 bar = 100 kPa.

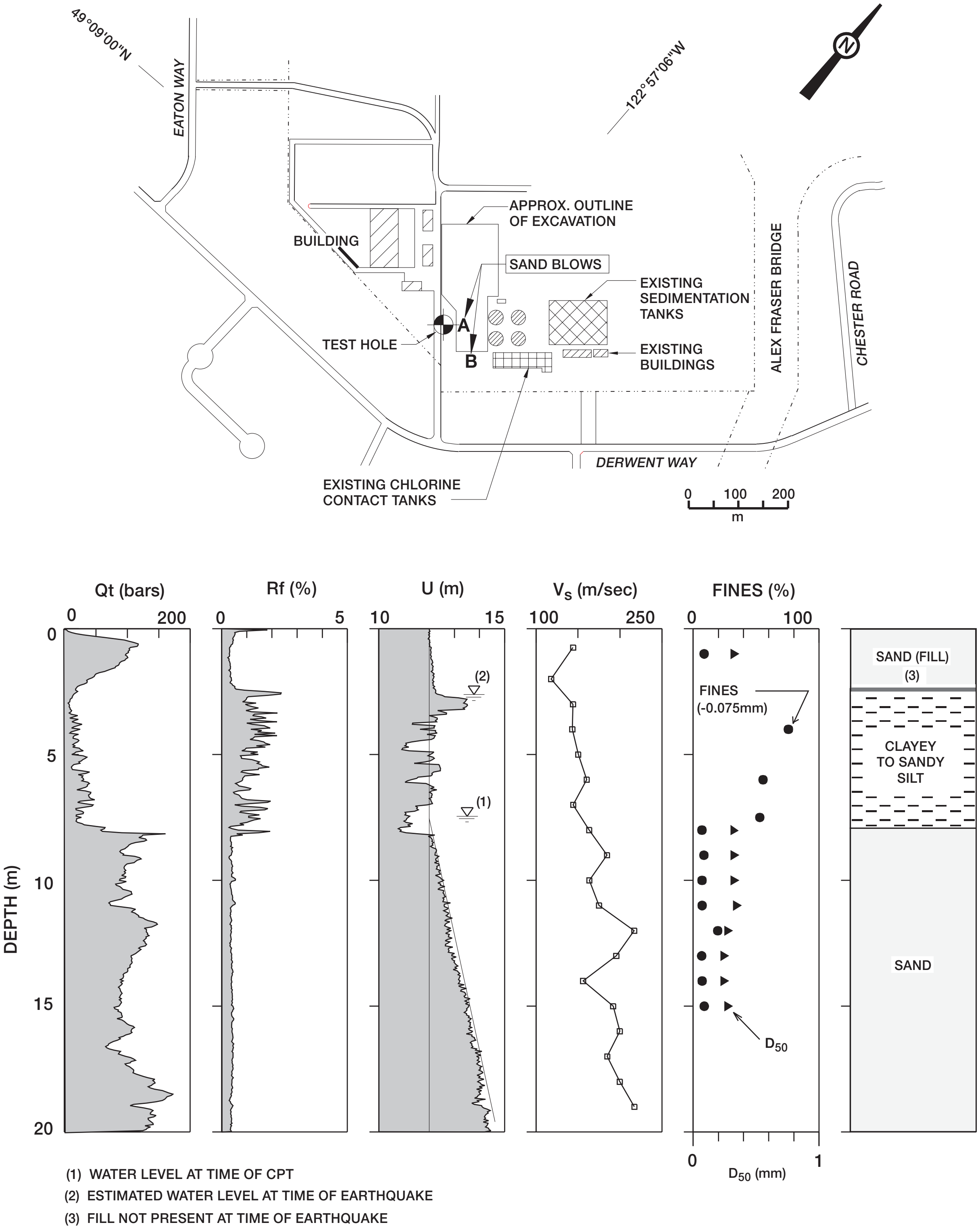


Table 1. Radiocarbon ages, Annacis Island.

Radiocarbon age (^{14}C years BP)[a]	δ^{13}C (‰)	Calibrated age (cal year BP)[b]	Laboratory No.[c]	Dated material
1680±60	—	1556 (1309–1872)	TO-4709	Plant leaves[d]
1780±80	–24.3	1633, 1647, 1694 (1528–1873)[e]	GSC-5865	Wood[f]
1790±60	–21.5	1635, 1645, 1706 (1536–1870)[g]	GSC-5857	Wood[h]
2000±60	–24.19	1905, 1928, 1941, 1946 (1820–2116)[i]	GSC-5983	Wood[j]

[a] Error terms are 2σ for Geological Survey of Canada ages and 1σ for the IsoTrace age. Ages are normalized to $\delta^{13} = -25.0$ ‰ PDB.

[b] Reference datum is AD 1950. Calibrated from decadal data set of Stuiver and Becker (1993), using the program CALIB 3.0.3 (Stuiver and Reimer 1993). The values in parentheses represent the 2σ age range using error multipliers of 1.5 (TO age) and 2.0 (GSC ages).

[c] GSC, Geological Survey of Canada; TO, IsoTrace Laboratory (University of Toronto).

[d] *Thuja plicata* leaves from the top of the paleosol beneath sand.

[e] There are three possible intercept calendric ages for a radiocarbon age of 1780 ± 80 ^{14}C years BP.

[f] *Pinus* sp. (GSC Wood Identification Report No. 94.100); branch or root at the top of the paleosol beneath sand.

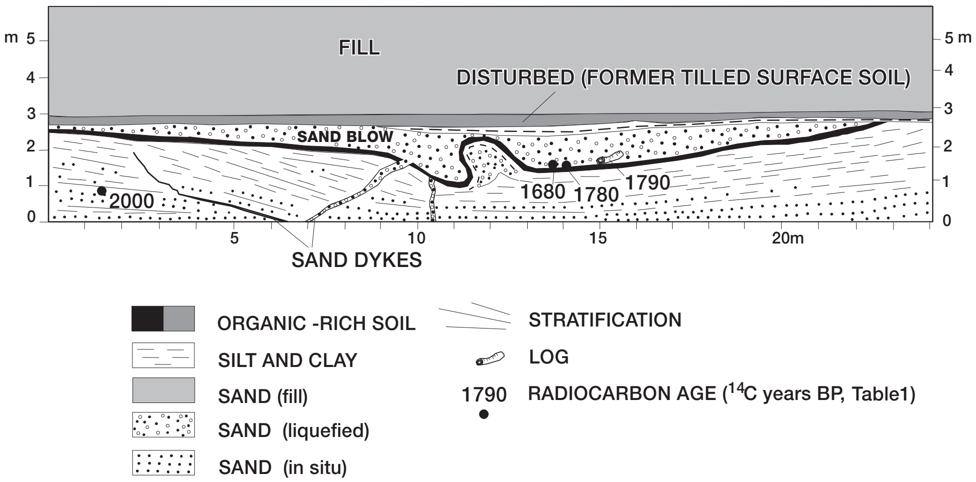
[g] There are three possible intercept calendric ages for a radiocarbon age of 1790 ± 60 ^{14}C years BP.

[h] *Thuja plicata* (GSC Wood Identification Report No. 94.90); outermost nine rings of a log with preserved bark resting on top of the paleosol beneath sand.

[i] There are four possible intercept calendric ages for a radiocarbon age of 2000 ± 60 ^{14}C years BP.

[j] *Picea* sp. (GSC Wood Identification Report No. 95.32); branch within sediments overlain by sand blow.

Fig. 3. Sketch of a large sand blow and feeder dykes exposed in the wall of an excavation on Annacis Island (site A, Fig. 2). Note the tight fold developed in the thin organic soil underlying the sand blow, and the gentle dip of injected sediments towards the centre of the structure.



The Fraser delta has formed since the disappearance of the last ice sheet 13 000 to 11 000 ^{14}C years BP (Clague et al. 1983). The postglacial deltaic sequence unconformably overlies Pleistocene stratified sediments, tills, and glaciomarine diamictons, and is locally more than 300 m thick (Clague et al. 1991; Luternauer et al. 1995). The surface sediments of the delta plain are floodplain and intertidal silts and silty sands, 3–15 m thick, and peat up to 8 m thick. These sediments overlie a unit of poorly graded, fine to medium sand that is 10–20 m thick, commonly has a sharp base with several metres of local relief, and fines upward. This unit is nearly continuous under the dyked delta plain and the inshore part of the western tidal flats, and was deposited in Fraser River distributary channels (Monahan et al. 1993). It is the source of most of the numerous sand dykes and sand blows that have been previously reported on the Fraser delta (Clague et al. 1992; Naesgaard et al. 1992), as well as those documented in this paper. The channel sands overlie a thick sequence of silty and sandy foresets and silty and clayey bottomsets, analogous to sediments presently being deposited on the Fraser delta slope (Clague et al. 1983, 1991; Luternauer et al. 1995).

Liquefaction features

Stratigraphic context and description

Sand dykes and sand blows were observed in a large, 6 m deep, dewatered pit dug during the expansion and upgrading of the Greater Vancouver Regional District, Annacis Island sewerage treatment facility (Fig. 2). The site is located near the southwestern end of Annacis Island (49°09.8′N, 122°57.1′W; geodetic surface elevation about 4 m), an island within the Main Channel of the Fraser River (Fig. 1). Two large sand blows and related feeder dykes were exposed in excavated faces near the southwest end of the pit during late 1994 and early 1995. Smaller dykes were present elsewhere in the pit, but were not studied in detail.

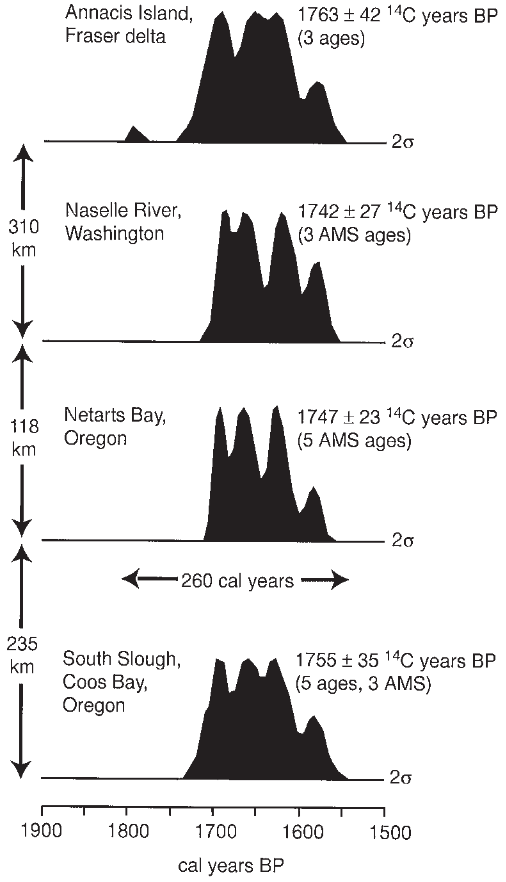
The uppermost 2.5–3 m of sediment is sand fill (Fig. 3). The fill sharply overlies a 20 cm thick, brown, organic-rich soil that marks the tilled surface of Annacis Island prior to industrial development. The soil, in turn, overlies and truncates a thin (<30 cm) unit of weakly bedded to massive, olive-grey, clayey silt. Two large sand blows underlie the clayey silt unit and the surface soil. The blows, which are up to 1 m thick and 25 m wide (Fig. 3), are tapering wedges of poorly graded, massive to weakly stratified, fine sand. The upper part of one of the wedges is finer than the lower part. The two wedges sharply overlie a thin (5–20 cm) layer of brown silty peat containing abundant detrital wood, conifer leaves, and in situ roots of woody plants (a buried organic soil or "paleosol"). A log (4+ m long, 15 cm in diameter) with preserved bark was found on the silty peat layer directly beneath the vented sand. The peat layer overlies interbedded, olive-grey silt and fine sand deposited in a fluvial overbank setting (Fig. 3). The upper part of this unit is mainly thinly bedded silt; sand beds increase in number and thickness towards the bottom of the exposure, and the lowest exposed sediments are silty sand and sand. Parts of the unit are rhythmically bedded, with couplets of silt and fine sand ranging from a few centimetres to about 10 cm thick. Stratification is parallel, but is locally truncated at low angles along broad shallow channels. Thick sand below the base of the pit is interpreted to be part of the distributary channel complex mentioned in the preceding section. This sand is more than 12 m thick at the study site (Fig. 2).

Sediments beneath the sand blows are deformed. The thin silty peat layer is buckled and overturned near the center of one of the blows; a bulbous mass of what is interpreted to be liquefied sand forms the core of this structure (Fig. 3). Layering in the interbedded silt–sand unit is also warped beneath the sand blow.

Numerous sand dykes, ranging in thickness from a few millimetres to about 25 cm, cut the sediments beneath the two sand blows (Fig. 3). The dykes are concentrated near the centres of the two sand blows where the intruded sediments are most deformed. Most of the dykes are steeply dipping, but some cut stratification at a low angle. The dykes have a complex three-dimensional form, pinching and swelling both vertically and horizontally, but, in general, they thin upward. A few of the dykes were traced from the base of the excavation, through the interbedded silt–sand unit and the silty peat layer, to the bottom of one of the sand blows. The intruded sand is similar in texture and mineralogy to the sand blows and to the in situ sand at the base of the excavation, which is probably the source.

There is no conclusive evidence for more than one liquefaction event at Annacis Island or, for that matter, at any of the other sites on the Fraser delta where sand dykes and blows have been found (Clague et al. 1992). There are cross-cutting dykes at some sites, but this could be the result of multiple injections during one earthquake rather than two separate events. If there had been two or more events, sand blows should occur at different stratigraphic levels, at least at some sites, and no such evidence has been found. This leads us to suggest that only one major episode of liquefaction may have occurred in the last 3500 years, which is the period spanned by the uppermost sediments of the Fraser delta. We qualify this conclusion, however, by noting that sand may have intruded along the same fractures during two or more earthquakes and may not have broken through the 3–4 m of clayey silt that caps much of the delta. Also, dating at sites other than Annacis Island is not precise enough to demonstrate that all of the features are the same age, although this is not precluded by the available data.

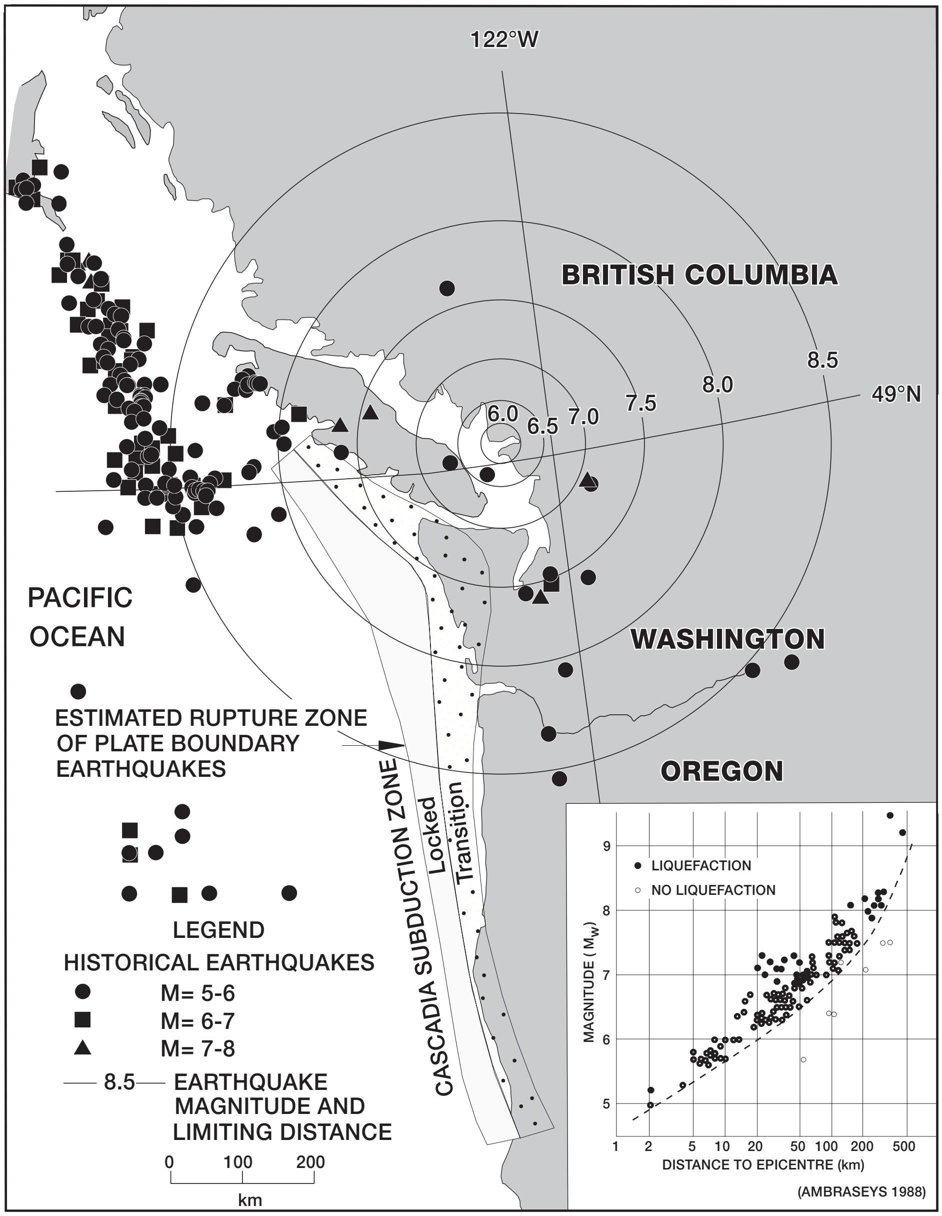
Fig. 4. Calibrated-age probability distributions for the mean of three ^{14}C ages from Annacis Island (Table 1) and for mean ages from coseismically subsided soils at three sites in Washington and Oregon. The probability distributions include 2σ age intervals calculated using the decadal calibration data set of Stuiver and Becker (1993) (method of Stuiver and Reimer 1993). An error multiplier of 1.0 was applied to accelerator mass spectrometry (AMS) ages (Nelson et al. 1995) and 1.5–2.0 to other radiocarbon ages (note: error multipliers expand laboratory-quoted errors to cover uncertainties in reproducibility and systematic bias; for a discussion, see Stuiver and Pearson 1993). The numbers next to distributions are the mean and standard deviation of averaged ages and, in parentheses, the number of ages. Vertical arrows show distances between sites; South Slough is 650 km south of Annacis Island. Mean ages from all sites are statistically indistinguishable (test of Ward and Wilson 1978).



Age

Four radiocarbon ages, including three from samples resting on the paleosol beneath the vented sand, provide unusual chronological control on the liquefaction event at Annacis Island (Fig. 3; Table 1). A branch collected from sediments that are cut by the sand dykes was dated at 2000 ± 60 ^{14}C years BP; this is a maximum, but not closely limiting, age for liquefaction. The outermost nine rings of a log with preserved bark that was lying on the ground surface (i.e., on the paleosol) when it was

Fig. 5. Map of the Pacific Northwest showing, as concentric circles, maximum distances that earthquakes of different magnitudes can be from Annacis Island while still causing liquefaction there (based on the relationship of Ambraseys 1988; inset). Moderate and large historical earthquakes and the inferred source zone of great plate-boundary earthquakes on the Cascadia subduction zone (adapted from Hyndman and Wang 1993, Fig. 1) are also shown. M, magnitude.



buried by vented sand gave an age of 1790 ± 60 ^{14}C years BP. Because fallen trees in the Vancouver area rapidly lose their bark due to exposure and bacterial decay, the dated log probably had not been dead for more than a few decades before it was buried. Thus, the outer-ring age is a closely limiting, maximum age for liquefaction. It is in agreement with two other radiocarbon ages from the top of the paleosol directly below vented sand: one of 1780 ± 70 ^{14}C years BP on a branch or root and another of 1680 ± 60 ^{14}C years BP on western redcedar (*Thuja plicata*) leaves. The three ages meet the criteria for statistical contemporaneity of Ward and Wilson (1978); their weighted mean is 1763 ± 42 ^{14}C years BP, which corresponds to a calendric age range of 1542–1815 cal years BP (2σ limits; Fig. 4, Table 1).

Origin

The sand dykes and sand blows at Annacis Island resemble similar features found at many other sites on the Fraser delta that have been attributed to earthquakes (Clague et al. 1992; Naesgaard et al. 1992). The Annacis Island features, however, are of particular interest because of their large size and because they have been more precisely dated than liquefaction features at other sites.

Clague et al. (1992) reviewed possible causes of liquefaction on the Fraser delta and concluded that the sand dykes and blows that occur there are probably seismically generated. Notably, the Fraser delta features meet several criteria required to demonstrate a seismic origin (Obermeier et al. 1990): (1) They show "evidence for an upward-directed, strong hydraulic force that

Table 2. Calculated probabilities of liquefaction.

Seismic model[a]	Magnitude scaling method[b]	Ground response amplification[c]	Annual probability of liquefaction[d]	Liquefaction return period (a)[d]
NBCC	Seed	Yes	0.547×10^{-2}	183
BC Hydro	Seed	Yes	0.523×10^{-2}	191
NBCC	NCEER	Yes	0.411×10^{-2}	243
BC Hydro	NCEER	Yes	0.314×10^{-2}	318
NBCC	Seed	No	0.290×10^{-2}	345
BC Hydro	Seed	No	0.243×10^{-2}	412
NBCC	NCEER	No	0.226×10^{-2}	442
BC Hydro	NCEER	No	0.148×10^{-2}	676

[a] NBCC, National Building Code of Canada seismic model, with Hasegawa et al. (1981) attenuation (Basham et al. 1982); BC Hydro, B.C. Hydro and Power Authority seismic model, with Crouse (1991) and Idriss (1993) attenuations (Little 1993). The two seismic models are based on historical seismicity and regional tectonic features; neither incorporates great plate-boundary earthquakes on the Cascadia subduction zone.

[b] Seed, Seed et al. (1983); NCEER, National Center for Earthquake Engineering Research committee draft recommendations (Finn 1996).

[c] Yes: incorporates ground-response amplification factor of Borcherdt (1994), calculated assuming a shear-wave velocity of 182 m/s for the upper 30 m and a reference shear-wave velocity of 555 m/s; this gives values that vary with ground acceleration, but are commonly about 1.4. No: no ground-response amplification.

[d] Liquefaction probabilities and return periods were calculated with a modified version of the program EQRISK, using the method of Seed and de Alba (1986) and the SCPT penetration resistance at 9.4 m depth (Fig. 2); the calculations include a 1σ offset on the attenuation relationship.

was suddenly applied and of short duration." (2) They resemble liquefaction features generated by historical earthquakes in similar settings (Obermeier 1984; Obermeier et al. 1990; Tuttle et al. 1990; Sims and Garvin 1995). (3) They are not located in areas where other phenomena, notably artesian discharge, might produce similar features. (4) They probably formed in one or more discrete, short episodes that individually affected a large area; these episodes were separated by lengthy periods during which no such features formed.

Additional evidence that the liquefaction was caused by an earthquake comes from sites along the Serpentine River just south of the Fraser delta (Fig. 1). There, liquefaction occurred at the same time as a sudden change in land level (Mathewes and Clague 1994). At one of the Serpentine sites, a mound of vented silt separates freshwater peat from overlying tidal clayey silt. The clayey silt was deposited on a submerged peaty wetland soon after the liquefied sediment was vented, suggesting that both submergence and liquefaction resulted from an earthquake. Submergence of about the same age has been documented at many other coastal sites, both in the Vancouver area and on southern Vancouver Island (Mathewes and Clague 1994). Mathewes and Clague (1994) concluded that the earthquake responsible for this submergence occurred about 1900 years ago. However, the radiocarbon ages that most closely date the submergence are maxima, and the earthquake could be as much as a few centuries younger than Mathewes and Clague thought. This submergence and the sand dykes and blows at Annacis Island were probably produced by the same earthquake.

Liquefaction assessment

Here we consider the possible range of earthquake magnitudes and source distances that could generate the sand dykes and sand blows at Annacis Island. We also compare the frequency of liquefaction events inferred from field observations and dating with the frequency calculated using current seismic models and liquefaction assessment procedures.

Magnitude – source distance relationship

Ambraseys (1988) developed an empirical relationship between earthquake magnitude and the maximum distance from the epicentre of liquefaction (Fig. 5 inset). We used this relationship to define areas within which earthquakes of different magnitudes might cause liquefaction at Annacis Island (shown as concentric circles centered on Annacis Island in Fig. 5). This plot suggests the following:

(1) a great plate-boundary earthquake may be responsible for the sand dykes and sand blows on the Fraser delta;
(2) the earthquake that caused the liquefaction on the Fraser delta had a minimum magnitude of 6, assuming that all sand dykes and blows on the delta (Fig. 1) are the same age; and
(3) there is only one historical earthquake in the Pacific Northwest (a magnitude 7.4 event in northern Washington in 1872; Malone and Bor 1979) that possibly could liquefy Fraser delta sediments. However, the exact magnitude and location of this event are uncertain.

Probability of liquefaction

The probability of liquefaction at Annacis Island was calculated from seismic cone-penetration test (SCPT) data (Fig. 2), using two seismic source models: the National Building Code of Canada (NBCC) model (Basham et al. 1982) and the B.C. Hydro and Power Authority model (B.C. Hydro and Klohn Leonoff Ltd. 1992; Little 1993). Both models are probabilistic in nature and are based on historical seismicity and on seismic source zones defined from regional tectonic features. Neither model includes great plate-boundary earthquakes because such earthquakes have not occurred during historical time; including such earthquakes would increase the calculated probability of liquefaction.

Liquefaction was assessed according to the method of Seed and de Alba (1986), using both the original magnitude scaling factors of Seed et al. (1983) and the more recent factors recommended by a committee of the National Center for Earthquake Engineering Research (NCEER) (Finn 1996). The stress reduction factor (r_d) of Byrne and Anderson (1987) for a typical Fraser delta sediment profile was employed. Ground-response amplification was included in the analysis using the procedure of Borcherdt (1994). SCPT data were corrected so that they would be representative of the ground-surface and water-table conditions about 1700 years ago (i.e., effects of the surface fill and pumping of water at the site were removed). Probabilities of liquefaction, shown in Table 2, were calculated with the computer program EQRISK (McGuire 1976), modified to incorporate Seed and de Alba's liquefaction assessment procedure. Epistemic uncertainties in the seismic and liquefaction models were not considered in the analysis.

The results of the above analysis indicate that if there has been only one major liquefaction event on the Fraser delta in the last 1700 years, the liquefaction assessment procedure currently used in the region (Fraser Delta Task Force 1991) overestimates liquefaction risk (Table 2, row 1). This procedure uses the NBCC seismic model, median + 1σ attenuation values, Seed and Idriss's magnitude scaling factors, and ground-motion amplification of approximately 1.4. Use of the more recent B.C. Hydro seismic model with NCEER magnitude scaling factors gives larger return periods, but the values are only about half those inferred from field evidence (Table 2).

Discussion

There have been 10 moderate to large (magnitude 6–7.5) earthquakes within the North America and Juan de Fuca plates in southwestern British Columbia and western Washington in the last 150 years (Shedlock and Weaver 1988; Rogers 1995). Most of these crustal and subcrustal earthquakes have caused localized liquefaction near their epicentres, although no instances of liquefaction have been reported on the Fraser delta. This is consistent with the empirical data of Ambraseys (1988) and the analysis of the Annacis Island test-hole data, both of which indicate that the Fraser delta is too far from the epicentres of recent earthquakes to have experienced significant liquefaction. As mentioned previously, liquefaction on the scale of that at Annacis Island appears to be a rare occurrence: there is no evidence on the Fraser delta for more than one major liquefaction event in the last few thousand years, although such evidence may yet be found. This raises two related questions that have important implications for earthquake hazard assessment: is the liquefaction recorded at Annacis Island and elsewhere on the Fraser delta the result of an earthquake of the same size as the largest historical events in the region, but with an epicentre close to Vancouver? or do the features record a much larger (magnitude 8 or 9) distant earthquake at the plate boundary?

The evidence from the Fraser delta does not allow us to definitively answer these questions, but it is possible that the earthquake that generated the sand dykes and blows at Annacis Island, and probably at other sites on the delta, is the plate-boundary earthquake that caused tidal wetlands along the Pacific coast of Washington and Oregon to subside about 1500–1700 years ago (Atwater 1992; Darienzo et al. 1994; Atwater and Hemphill-Haley 1996; Nelson et al. 1996*a*). Because great earthquakes at some subduction zones have occurred only hours or days apart, radiocarbon dating cannot demonstrate that buried organic soils of the same radiocarbon age subsided at exactly the same time (Atwater 1992; Darienzo et al. 1994; Nelson et al. 1996*a*). However, researchers have recently suggested that the evidence of sudden subsidence and tsunamis within a few hundred years of 1700 calendar year BP at many estuaries in southern Washington and Oregon records the same earthquake (Darienzo and Peterson 1995; Nelson et al. 1996*b*; Atwater and Hemphill-Haley 1996).

A great plate-boundary earthquake (or earthquakes) 1500–1700 years ago has been most precisely dated at three estuaries, as much as 350 km apart, in Washington and Oregon (Figs. 1, 4). The weighted mean of three accelerator mass spectrometry (AMS) radiocarbon ages on herbaceous plants rooted in the top of a buried marsh soil at Naselle River, Washington, is 1742 ± 27 ^{14}C years BP. Five ages on rooted plants were obtained at this site, but the oldest two ages were not included in the mean because they did not meet Ward and Wilson's (1978) criteria for contemporaneity. Two AMS ages on rooted plants and three AMS ages on conifer buds and leaves from a correlative marsh soil at Netarts Bay, Oregon, have a mean age of 1747 ± 23 ^{14}C years BP. The mean of three AMS ages on similar materials from the top of a buried marsh soil described by Ota et al. (1995) at South Slough, Coos Bay, Oregon, is 1736 ± 48 ^{14}C years BP. If two additional gas-proportional radiocarbon ages from a nearby correlative soil studied by Nelson et al. (1996*a*) are included, the mean for South Slough becomes 1755 ± 35 ^{14}C years BP. These means compare well with the mean of the three ages from the top of the paleosol at Annacis Island (1763 ± 42 ^{14}C years; Table 1, Fig. 4). The ages used to calculate the means at each site, as well as the mean ages themselves, are statistically indistinguishable at the 2σ level. Calibration of the means from each site yields intervals that span more than 200 years (Fig. 4), an interval far too long to preclude the occurrence of a series of magnitude 8, plate-boundary earthquakes along the subduction zone, rather than a single magnitude 9 earthquake. Moreover, many of the radiocarbon ages are on detrital material that grew before the organic soil subsided and was buried, and thus are maxima for the time of the earthquake (or earthquakes). However, recently reported, high-precision, gas-proportional ages on fossil plants in growth position from a site along Niawiakum River in southern Washington (Fig. 1) support an age of 1500–1700 cal years BP for this earthquake (Atwater and Hemphill-Haley 1996).

An alternative hypothesis, which is also consistent with the radiocarbon data, is that the earthquake responsible for the liquefaction at Annacis Island was a crustal event of about the same age as (i.e., within about 200 years of) a larger plate-boundary earthquake to the west. The two earthquakes could be related, with minutes, days, or years separating them, or they could be completely unrelated. We favour this alternative hypothesis because the subsidence that is inferred to have accompanied the earthquake is more consistent with displacement on a crustal fault than with plate-boundary rupture

(Mathewes and Clague 1994). Widespread, subsidence during a great plate-boundary earthquake would probably not extend as far east as Vancouver; rather, it would be limited to western Vancouver Island and to the Pacific coast of Washington, Oregon, and northernmost California (Hyndman and Wang 1993). Contemporaneous slip on faults in the North America plate and on the plate boundary has been advanced as a possible explanation for inferred coseismic deformation in the southern Puget Lowland of Washington (Bucknam et al. 1992), in southern Oregon (McInelly and Kelsey 1990; Nelson 1992), and in northern California (Clarke and Carver 1992). Sudden uplift along one or more crustal faults in the Puget Lowland about 1000 years ago (Bucknam et al. 1992; Bucknam and Biasi 1994) may have occurred at the same time as localized subsidence and venting of sand on the Pacific coast; the subsidence and venting may be due to plate-boundary rupture (Atwater 1992).

The liquefaction analysis does not allow us to rule out a plate-boundary or crustal source for the earthquake that caused the liquefaction at Annacis Island. It does, however, confirm that liquefaction-prone strata are present at the site. Ambraseys' data indicate that a magnitude 8 or larger earthquake centered on the northern Cascadia subduction zone could liquefy sediments at Annacis Island. The data also indicate that the minimum magnitude of the earthquake that produced the liquefaction features on the Fraser delta, assuming that all of these features are the same age, is about 6. If only one earthquake has caused significant liquefaction within the last 1700 years, which our field observations and dating show is possible, current seismicity and liquefaction assessment procedures may overestimate liquefaction risk. We temper this statement by reiterating that evidence for more than one liquefaction event may yet be found in new excavations on the Fraser delta.

Conclusion

Sand dykes and sand blows at Annacis Island record liquefaction during a large earthquake about 1700 years ago. This earthquake is probably the largest to have affected south-coastal British Columbia in the last few thousand years. It may be a great plate-boundary earthquake on the Cascadia subduction zone, which produced coseismic subsidence along the Pacific coast of Washington and Oregon 1500 to 1700 years ago, or it may be a crustal earthquake of about the same age. The data from Annacis Island, together with information from other sites on the Fraser delta, suggest that earthquakes capable of producing extensive liquefaction in this area are relatively rare events.

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