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Evidence for Late Holocene Tsunamis at Catala Lake, British Columbia

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ABSTRACT

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Thin sheets of sand and gravel occur within a sequence of fine organic-rich sediments at Catala Lake, off the west coast of Vancouver Island, British Columbia. The uppermost of these coarse sheets thins and fines landward away from the lake outlet, consistent with deposition by a tsunami. This coarse sediment sheet has been radiocarbon dated to some time after AD 1655; we suggest that it was deposited in 1700 by the tsunami of the last great earthquake at the Cascadia subduction zone. Abundant plant macrofossils, derived from nearby forest, are present within and on top of the sand and gravel layer, suggesting that the tsunami transported forest-floor litter, mosses, and seeds into Catala Lake. Deposition coincided with abrupt changes in diatom and foraminifera communities in the lake. The post-tsunami diatom assemblage is more marine in character than the immediate pre-tsunami assemblage, and the foraminifera community became more diverse after the tsunami. These changes are due either to coseismic subsidence or erosion of the outlet by the tsunami, which increased tidal exchange between the sea and the lagoon that was the precursor to Catala Lake. Older coarse sediment layers in cores from Catala Lake and the bordering marsh may also be tsunami deposits. One of these layers is about 1,000 years old and dates to the time of the penultimate great Cascadia earthquake.

ADDITIONAL INDEX WORDS: *tsunamis, paleoseismology, earthquakes, sedimentology, pollen, diatoms, foraminifera, Cascadia subduction zone, British Columbia.*

INTRODUCTION

Historical records and coastal geologic studies show that large tsunamis have struck the west coast of North America. The most recent large tsunami occurred in 1964 and was generated by a great earthquake (moment magnitude 9.2) centered in southern Alaska (Hansen *et al.*, 1966). This tsunami caused considerable damage along the Pacific coast as far south as California (Wigen and White, 1964; Hansen *et al.*, 1966; Murty and Boilard, 1970), and left a thin deposit of sand, silt, and plant detritus in some coastal marshes on Vancouver Island (Clague and Bobrowsky, 1994; Clague *et al.*, 1994; Benson *et al.*, 1997). Equally large tsunamis, which predate initial European exploration of the Pacific Northwest in the late 1700s, were triggered by great earthquakes (magnitude 8+) on the boundary between the Juan de Fuca and North America plates (Cascadia subduction zone, Figure 1a). The most recent of the earthquakes, which is particularly well documented at about 20 estuaries between Vancouver Island and northern California (Atwater *et al.*, 1995; Nelson and Personius, 1996), occurred in AD 1700 (Satake *et al.*, 1996).

Tsunamis triggered by great earthquakes at the Cascadia subduction zone have left landward-thinning sheets of sand and gravel in some tidal marshes and low-lying coastal lakes (Atwater *et al.*, 1995, and references therein; Kelsey *et al.*, 1994; Nelson *et al.*, 1996, Hutchinson *et al.*, 1997). The most complete record of Cascadia tsunamis comes from Bradley Lake on the southern Oregon coast. A sequence of fine-grained sediments at Bradley Lake spans the last 7,500 years and contains numerous landward-fining and landward-thinning sheets of sand and/or coarse organic debris (Kelsey *et al.*, 1994; Nelson *et al.*, 1996). The sand/organic debris layers were deposited when tsunami waves overtopped a dune that separates the lake from the Pacific Ocean. Radiocarbon dating of these layers has shown that they are probably the same age as earthquakes dated elsewhere in Cascadia from buried soil sequences (Atwater, 1996; Atwater and Hemphill-Haley, 1997). The average recurrence interval for the earthquakes and tsunamis is about 500 years, but successive

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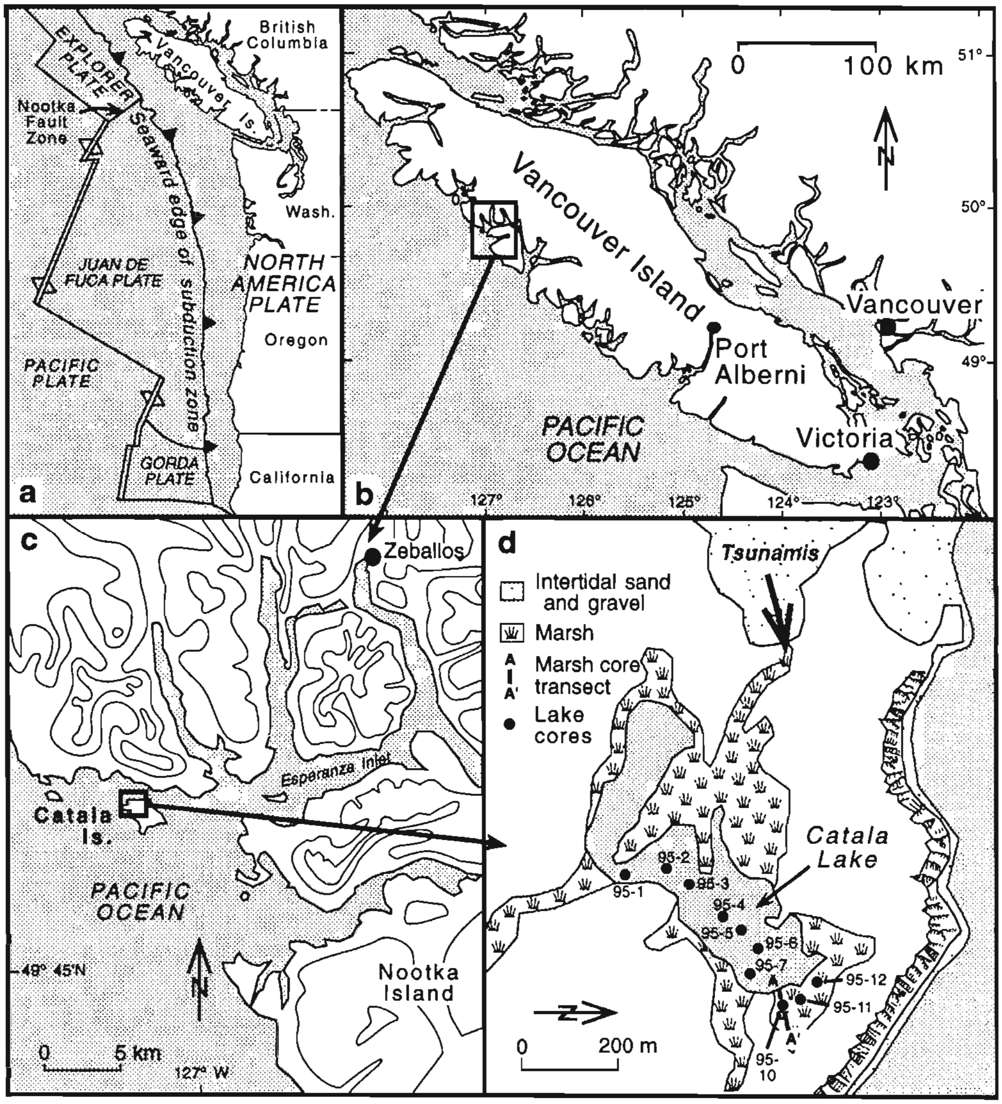

Figure 1. The study area. (a) shows lithospheric plates mentioned in the text. Topographic contour interval in (c) is 305 m (1,000 ft). Numbered sites in (d) locate sections depicted in Figures 3 and 4.

events may be separated by as little as a century to more than 1,000 years.

Less complete records of Cascadia tsunamis have been obtained from marshes and lakes on western Vancouver Island (CLAGUE and BOBROWSKY, 1994; BENSON *et al.*, 1997; HUTCHINSON *et al.*, 1997). The tsunamis of the most recent earthquakes in this region are reasonably well documented, but little is known about older events, mainly because much of western Vancouver Island, where one would expect to find evidence for tsunamis, is rising relative to the sea at a rate of about 1 m per 1,000 years (CLAGUE *et al.*, 1982; FRIELE and HUTCHINSON, 1993). Tsunami sands deposited in tidal marshes more than about 1,000–2,000 years ago have since been elevated above the limit of tides and either destroyed by erosion in the supratidal zone or covered by forest. Sands deposited in coastal lakes more than 1,000–2,000 years ago likewise have been elevated; the lakes may now be beyond the influence of tsunamis (HUTCHINSON *et al.*, 1997). Old tsunami deposits are undoubtedly present in some low-elevation lakes that were tidal inlets or lagoons when the tsunamis occurred, but such deposits are difficult to distinguish from other relatively coarse sediments that accumulate in such environments. Data from Port Alberni (Figure 1b), a site where there has been little or no uplift during late Holocene time, suggest that the average recurrence for large tsunamis (*i.e.*, those at least as large as the 1964 Alaska tsunami) on western Vancouver Island is about 400–500 years (CLAGUE and BOBROWSKY, 1994). This statistic incorporates not only local tsunamis gener-

Figure 2. Oblique aerial photograph of Catala Lake and Catala Island; view west.

ated by earthquakes at the Cascadia subduction zone, but also far-travelled tsunamis with sources elsewhere in the North Pacific Ocean.

With an average recurrence of 400–500 years, large tsunamis pose a significant hazard to people and property on the Pacific coast. By documenting the grain-size distribution, structure, and distribution of tsunami deposits, one can gain an understanding of the size, velocity, and run-up of the waves. This information is useful for predicting local run-up and the possible effects of future tsunamis, and, thus, gaining an understanding of the severity of the hazard. The information can also be used to test and refine computer-based models of tsunami propagation and run-up, several of which have been applied in Cascadia (HEBENSTREIT and MURTY, 1989; NG *et al.,* 1990, 1991; WHITMORE, 1993).

We and others have studied tsunami deposits in marshes, lakes, and inlets on western Vancouver Island (CLAGUE and BOBROWSKY, 1994; BENSON *et al.,* 1997; HUTCHINSON *et al.,* 1997). In this paper, we present results from a small, low-elevation lake on Catala Island off the west coast of Vancouver Island (Figure 1b–d). Our objectives are to (1) describe the sedimentology and fossil assemblages of tsunami deposits at Catala Lake, (2) relate the sequence of tsunami deposits to inferred earthquakes elsewhere along the Cascadia subduction zone, and (3) document paleoecological changes that accompanied the tsunamis.

STUDY SITE

Catala Island is located at the mouth of Esperanza Inlet, a fiord on central western Vancouver Island (Figure 1c). The island lies to the north of the Nootka fault zone, which marks the northern end of the subducting Juan de Fuca plate (Figure 1a). It has an area of about 2.5 km^2 and is almost entirely below 10 m elevation. Rocky reefs, rock cliffs, and gravelly and boulder beaches form the shoreline. Sand is uncommon along the shore, although it is present on at shallow depths on the seafloor surrounding the island.

Catala Lake (Figure 2) lies on the north-central part of Catala Island, is about 9 ha in area, and has a maximum depth of 1 m. Recharge is by direct rainfall and by surface and subsurface seepage. Rock crops out locally along the lake shoreline, but much of the lake margin is marsh. The lake drains northwest to the sea via a channel some 500 m long. This channel was dry during our two visits in the summer and fall of 1995. Marsh-covered gravel splays impound the lake, and choke the channel, at the outlet. Farther to the west, a tree-covered, gravel-boulder bar borders the bay at the mouth of the outlet stream. The high points of both of these littoral features are estimated to be 2–3 m above the upper limit of tides, and the surface of Catala Lake itself is less than 1 m above high tide level.

Tides at Catala Island are mixed semidiurnal with an estimated mean range of 2.9 m and a large range of 4.5 m

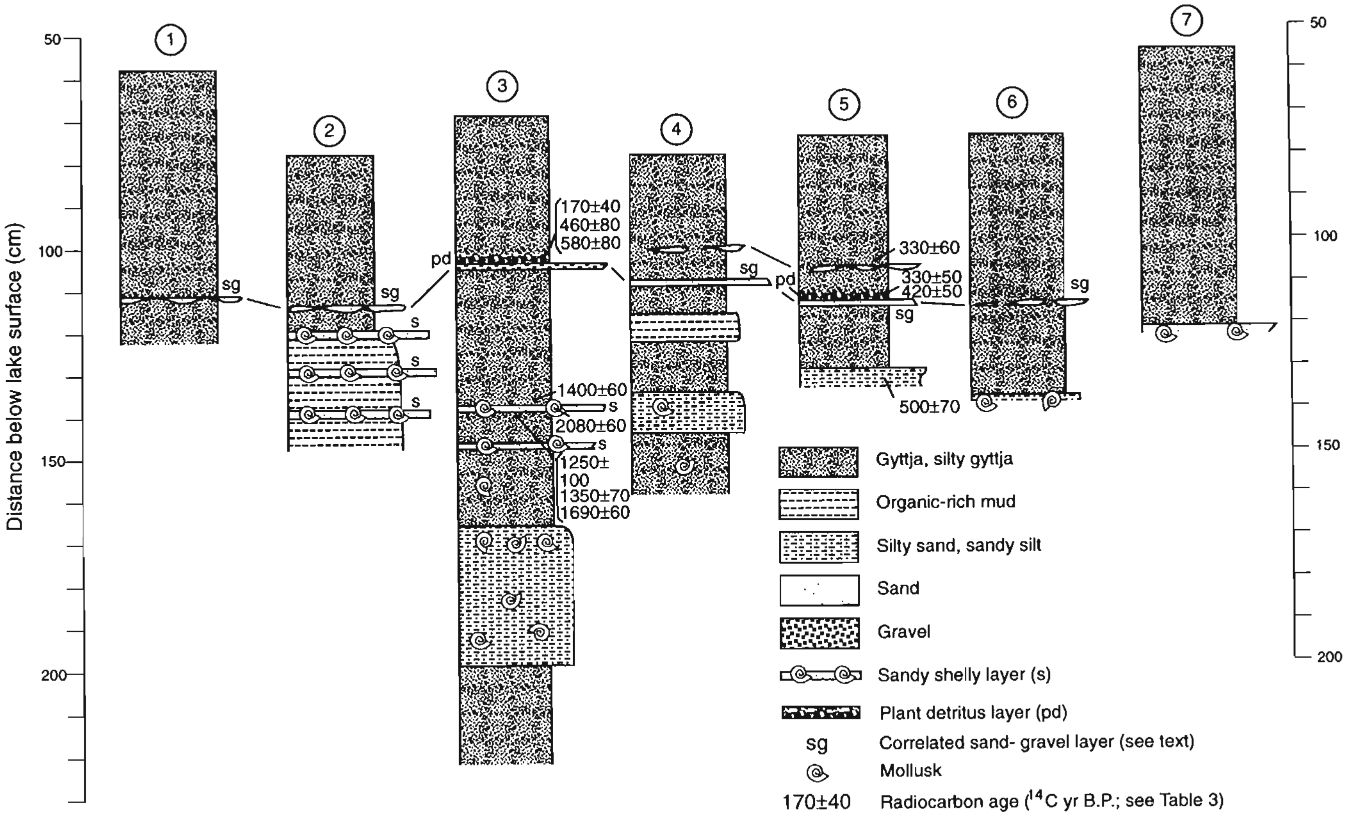

Figure 3. Stratigraphy of Catala Lake cores (see Figure 1d for locations).

(Fisheries and Oceans, 1997). Wind-driven waves on the exposed western shore of the island can be more than 5 m high (Thomson, 1981), but they are much smaller in bays and never reach inland as far as Catala Lake.

METHODS

We obtained cores at seven sites in Catala Lake and at 15 sites in the marsh bordering the lake on the northeast (Figure 1d). Marsh cores were collected in June 1995, mainly using a gouge corer. At one site, a 10-cm-diameter core was recovered by pushing an aluminum irrigation pipe through the marsh sequence. Lake cores were collected in September 1995 with a Livingstone piston corer operated from a platform consisting of two inflated boats.

Elevations of the marsh core sites, relative to the June 1995 surface of Catala Lake, were measured with a surveying level. The water depth of each lake core site was measured in September. This allowed us to tie the levels of the lake cores to those of the marsh cores. The level of the lake in September, however, was higher than in June; this difference, although not directly measured, is estimated to be 10 cm.

Observations made on the core material include sediment texture, structure, color, and organic constituents, as well as contact depths and characteristics. Samples were taken from one of the lake cores (no. 3, Figure 1d) for diatom, foraminifera, and plant macrofossil analysis, and from two lake cores and the large-diameter marsh core for radiocarbon dating. Samples of wood, bark, conifer needles, a pelecypod valve, and mussel fragments were dated by accelerator mass spectrometry (AMS) at IsoTrace Laboratory (University of Toronto). Approximate calendric ages were determined from the AMS ages using the decadal dendrocalibrated data of Stuiver and Becker (1993) and the marine dataset of Stuiver and Braziunas (1993).

Samples for diatom analysis were taken from the inferred tsunami deposits, from gyttja immediately above and below these deposits, and at 4 cm intervals through the remainder of the upper part of lake core 3 (Figure 3). Organic matter was removed from each of the diatom samples by H_2O_2 digestion, and the remaining material was dispersed in 250 ml of distilled water. After repeated decanting and settling to remove fines and to bring the solution to a near-neutral pH, aliquots of suspended material were dried on glass slides and mounted in Hyrax. The diatom assemblage of each sample was determined under a microscope at 1,000 × magnification by counting the first 200–300 specimens encountered in random parallel traverses. Taxonomic identifications are based on descriptions in Van der Werff and Huls (1957–74), Hendey (1964), Patrick and Reimer (1966, 1975), Rao and Lewin (1976), Foged (1981), Laws (1988), and Hemphill-Haley (1993). Species were placed in salinity-tolerance classes following the Halobian system of KOLBE (1927), as modified by HUSTEDT (1953). Changes in the lake environment were reconstructed from the range of salinity tolerance exhibited by the diatoms and ecological information in the diatom literature.

Thirty three subsamples from core 3 were analyzed for foraminifera and arcellacea (the latter are shelled, mainly freshwater protozoa; MEDIOLI and SCOTT, 1983). The subsamples were 2 cm thick (except those at 33–34.5 cm and 34.5–39 cm), and formed a continuous sequence from 11 to 80 cm depth. Nineteen of the 33 foraminifera samples were also analyzed for diatoms. The samples were agitated for one hour using a Burrell wrist shaker and washed on a 63 μm screen to eliminate fine sediment. All foraminifera and arcellacea were counted using an Olympus binocular microscope, usually at 40 × magnification.

Diatom and foraminiferal biofacies were determined separately from stratigraphically constrained cluster analyses (CONISS) of samples (GRIMM, 1987). A square-root transformation was employed to normalize species percent abundance data, and inter-sample similarity was determined by chord distance. A uniform total sum-of-squares value was used to determine cluster membership in the CONISS dendrogram.

Contiguous, mostly 2-cm-thick slices of sediment from 20 to 52 cm depth in core 3 were analyzed for plant macrofossils. Particular attention was paid to a distinctive layer of plant remains at 33–34.5 cm depth, directly above a layer of gravel. Subsamples of 10 ml volume were obtained by displacement in water and then gently washed through a 250 μm sieve under running water. The retained residue was examined under a dissecting microscope, and all identifiable plant remains were removed with tweezers and stored in 70% ethanol. Identification of conifer needles and seeds of vascular plants was done by comparison with a modern reference collection at Simon Fraser University. Mosses were identified by W.B. Schofield of the University of British Columbia.

LITHOSTRATIGRAPHY

Catala Lake Cores

The seven Catala Lake cores range in length from 62 to 154 cm (Figure 3). In this study, we were mainly interested in the upper, gyttja-rich part of the Catala Lake sediment sequence, thus, we collected relatively short cores. Refusal was not met at any of the core sites.

The cored sediments are mainly gyttja, organic-rich mud, sandy silt, and silty, very fine sand. The upper parts of all cores consist of dark grayish brown (2.5Y3/2–4/2, 10YR3/2), massive to weakly bedded gyttja. The gyttja contains abundant plant macrofossils (twigs, wood fragments, herbaceous plant tissue), especially in the uppermost 20–35 cm. At greater depths, plant macrofossils are less numerous, and the gyttja is more humified and contains more inorganic silt. Grayish brown to olive gray (5Y4/2), organic-rich mud, sandy silt, and silty sand are interlayered with the gyttja in the lower parts of several cores. Mollusk shells and shell fragments, and rare granules and small pebbles are present in some of the sandier zones.

A thin layer of sand and gravel (sg in Figure 3) occurs within gyttja at depths ranging from 30 to 55 cm in the cores. This layer is present in all lake cores except one, and apparently underlies at least 5 ha of the lake. It is thickest and coarsest adjacent to the lake outlet; at core site 3, about 50 m from the outlet, it is 2 cm thick and consists of poorly sorted, sandy granule gravel with well rounded stones. The layer thins and fines to the southwest and northeast away from the outlet. At the southernmost core site (no. 1), 160 m from the outlet, it is discontinuous, only a few millimeters thick, and consists of fine sand. The layer is absent at the northernmost core site (no. 7), 300 m from the outlet. Near the outlet, up to 2 cm of coarse plant detritus (pd in Figure 3) overlies the coarse layer (see section "Plant macrofossils" for a description of this material).

Other coarse layers (s in Figure 3) are present below layer sg in some cores. These layers are massive, moderately sorted, and typically 0.5–1 cm thick, although a 3-cm thick coarse bed forms the base of core 7. They consist of shell fragments and sand (generally as matrix). Small stones and coarse plant detritus are also present in some of these sediments. Although the coarse layers in several of the Catala Lake cores are similar, we are not able to confidently correlate these layers, due in part to insufficient chronological control. The layers, nevertheless, indicate that low-energy sedimentation in Catala Lake, which was then a lagoon (see "Biostratigraphy of Catala Lake Core 3"), was sporadically interrupted by short-lived, high-energy depositional events.

Marsh Cores

Thirteen cores were collected along a 60-m-long, east-west transect across the marsh at the northeast end of Catala Lake (Figures 1d and 4). One of the cores (the push core) is 253 cm in length; the others (gouge cores) are about 1 m long. Refusal was met only at core sites 10, 11, and 13, in gravel and pebbly mud. Two additional cores were collected from the marsh about 50 m and 100 m north of the transect (Figure 1d).

Five main stratigraphic units are recognized in the marsh cores. The uppermost unit, which is 61–82 cm thick, is grayish to yellowish brown (10YR4/2), fibrous peat containing abundant plant macrofossils (unit 1). Except in core 10, the peat gradationally overlies 14–34 cm of massive to weakly bedded, grayish brown to olive gray (2.5Y3/2–4/2, 10YR3/2), organic-rich mud (unit 2); in core 10, the peat sharply overlies gravel (unit 4; described below). The organic-rich mud gradationally overlies massive to laminated, olive gray (5Y4/2–5/2), clayey silt (unit 3). The clayey silt contains small amounts of disseminated sand and plant detritus, and rare granules and marine shells. In core 13, this unit is 153 cm thick and sharply overlies pebble gravel (unit 4) at 253 cm depth. Correlative gravel occurs at much shallower depth in core 10 (63 cm) and core 11 (83–84 cm). In core 10, the gravel is the lowest recovered material, but in core 11 it is underlain by 16 cm of massive, poorly sorted, pebbly sandy mud (unit 5). A 1-cm-thick layer of sandy granule also occurs within clayey silt at 223–224 cm depth in core 13.

A single layer of fine to very fine sand and silt (ss in Figure

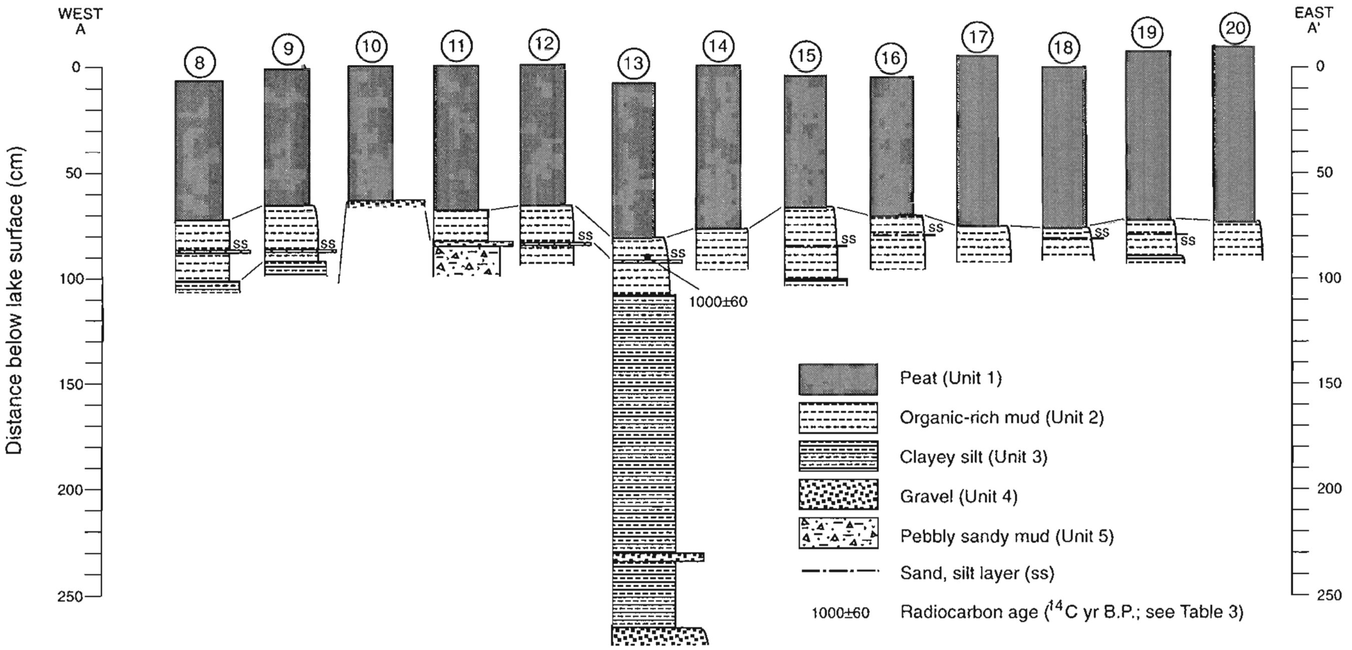

Figure 4. Stratigraphy of cores collected along transect AA′ across the marsh at the edge of Catala Lake (see Figure 1d for location). Distances between successive cores are about 5 m. The datum for the depth scale is the surface of Catala Lake in September 1995. The marsh was cored in June 1995 when the level of the lake was 1 cm below the surface of the marsh at site 8; however, the lake was about 10 cm higher in September (see text).

4) is present within unit 2 (organic-rich mud) in most marsh cores. This layer occurs over an area of at least 1 ha in this part of the marsh, but it has a maximum thickness of only 0.5 cm and occurs only as traces in many cores. The layer is thickest near the lakeshore and rapidly pinches out to the northeast, upslope and away from the lake.

BIOSTRATIGRAPHY OF CATALA LAKE CORE 3

Diatoms

Drainage from marshes surrounding Catala Lake produces acidic conditions. This is reflected in the dominance of acidophilic diatoms such as *Eunotia bidentula* in the surface sediments of the lake. In contrast, the diatom assemblages in Catala Lake core 3 are dominated by brackish and marine-brackish species (Figure 5, Table 1), indicating that a freshwater lake has become established only recently and that, prior to this, the basin was occupied by a tidal lagoon or saline pond.

On the basis of the cluster analysis, the Catala Lake diatom assemblages can be placed into seven biofacies (D1–D7, Figure 5). These biofacies can be further grouped into three developmental sequences that are separated by disturbance events related to the deposition of sand and gravel layers.

The youngest development sequence includes, from youngest to oldest, biofacies D1, D2, and D3. Biofacies D1 contains only fresh and fresh-brackish taxa, representative of the modern lacustrine environment. Biofacies D2 is a variable assemblage with a dominantly brackish affinity. The uppermost sample of D2 is dominated by *Fragilaria* species and contains few marine or brackish diatoms; it marks the transition to the modern freshwater lake. Sediment in the middle part of D2 contains abundant valves of the benthic species *Cocconeis costata* and *Cocconeis scutellum,* which occur as epiphytes in brackish-marine habitats. In contrast, the lower part of D2 is dominated by *Gyrosigma balticum,* a benthic diatom characteristic of brackish-water environments. Biofacies D3 contains abundant *Paralia sulcata,* a common coastal diatom with a complex life cycle. Its abundance in D3 indicates relatively saline waters. The Catala Lake basin, at the time of D3, was a marine-brackish pond or lagoon.

The D1–D3 developmental sequence was preceded by disturbance associated with the deposition of coarse layer sg (Figure 5). The coarse sediment has a diverse diatom assemblage similar to that of the immediately underlying gyttja. This suggests that the diatoms may be reworked from the gyttja.

Biofacies D4 and D5 constitute a second development sequence. Species characteristic of brackish-marine environments, such as *Achnanthes hauckiana, Navicula aequora,* and *Fragilaria construens,* dominate D4 and are also common in the upper part of D5. In contrast, D5, like D3, is dominated by the marine-brackish species *Paralia sulcata.* The D4–D5 developmental sequence, like sequence D1–D3, appears to record a successive freshening of the Catala Lake lagoon.

Disturbance prior to D5 is recorded by a shelly sand layer containing a diatom assemblage with strong marine affinities (s in Figure 5). *Paralia sulcata* accounts for more than 50% of this assemblage.

The earliest developmental sequence comprises biofacies

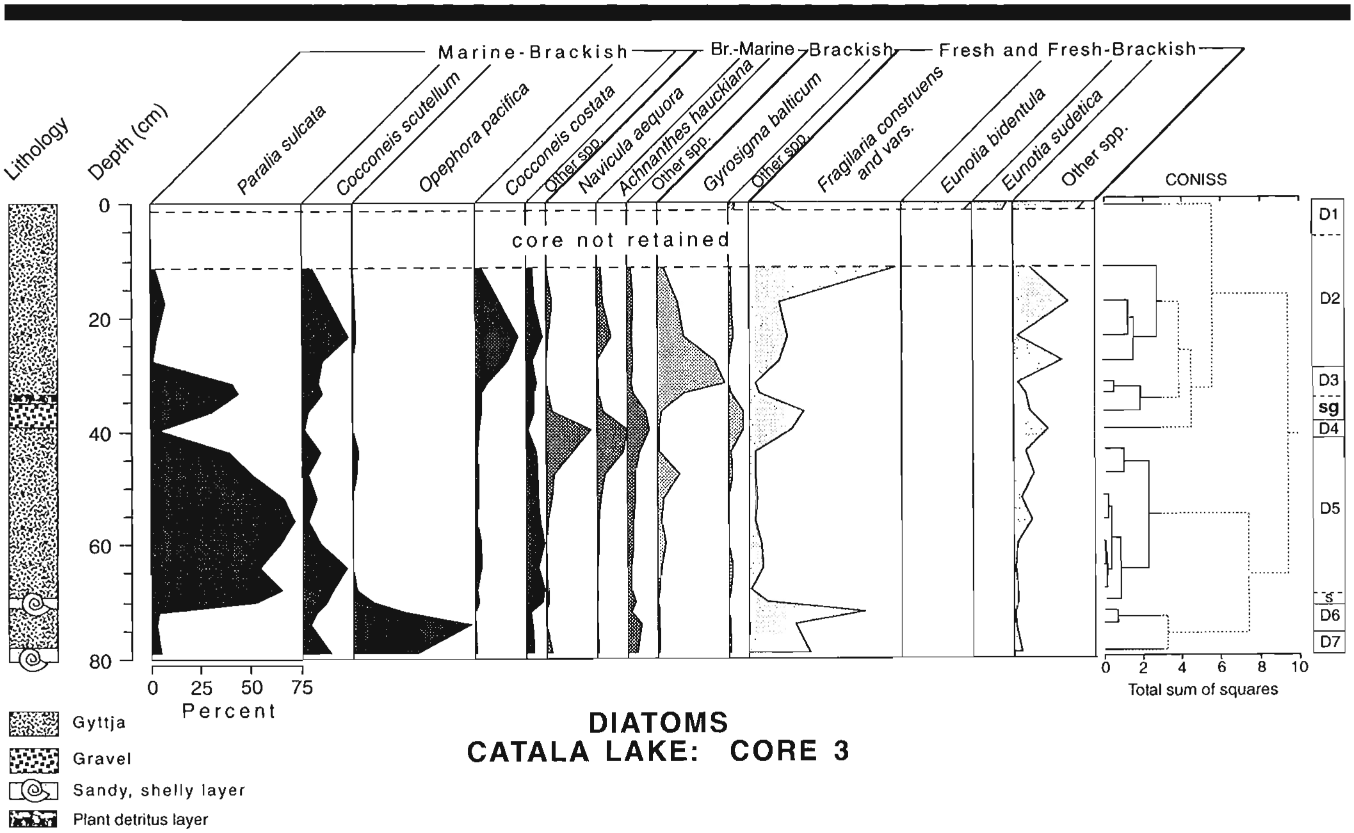

Figure 5. Diatom stratigraphy of the upper part of Catala Lake core 3, showing lithology, relative abundance of dominant taxa, results of the stratigraphically constrained cluster analysis (CONISS), and inferred diatom zones.

D6 and D7. *Fragilaria construens* is common in D6. This taxon is a pioneer species in freshwater habitats, but also can be found on intertidal sand flats. Biofacies D7 is based on a single sample from the basal sandy layer in the analyzed part of core 3. The diatom assemblage in this sample is dominated by valves of *Opephora pacifica* and *Fragilaria construens. Opephora pacifica* grows attached to sand grains and is abundant on intertidal sand flats in the Pacific Northwest. Developmental sequence D6–D7 records a lagoon subject to regular tidal flushing, with a slight freshening prior to the disturbance that left the shelly sand layer.

Foraminifera and Arcellacea

Foraminifera are present throughout the analyzed portion of core 3 (Figure 6, Table 2) *Miliammina fusca*, a common, subtidal and low marsh species on the British Columbia coast, is the most abundant foraminifer in most samples. Other common species in some samples include *Bucella frigida, Cribroelphidium excavatum, Haplophragmoides jeffreysei, Trochammina inflata, Trochammina ochracea,* and *Trochammina rotaliformis.*

Three foraminiferal zones biofacies were identified through cluster analysis (Figure 6). The boundaries between the biofacies are abrupt and correspond to sand and gravel layers.

The uppermost, *Trochammina rotaliformis* biofacies (F1, Figure 6) extends from the top of the core to the gravel layer at 34.5 cm depth. This biofacies is dominated by *Trochammina rotaliformis* and *Miliammina fusca*; *Trochammina ochracea* and *Trochammina inflata* are also present in most samples. The upper part of the biofacies contains freshwater arcellaceans, although one species found in this interval, *Centropyxis aculeata,* can tolerate salinities of up to 5‰. Because the arcellaceans occur together with foraminifera, they probably are allochthonous and have been washed into an increasingly freshening body of water from adjacent marshes.

A *Miliammina fusca* biofacies (F2) occurs in the core between the gravel layer at a depth of 34.5–39 cm and the sand layer at 69 cm. The low-diversity foraminifera fauna in this interval is overwhelmingly dominated by the euryhaline species *Miliammina fusca.* Faunas of this sort are typically found in organic-rich subtidal environments with salinities less than 20‰ (SCOTT *et al.*, 1980; ALVE, 1990). The absence of *Eggerella advena,* another species characteristic of brackish environments, suggests that salinities may been considerably less than 20‰ (SCOTT *et al.*, 1980).

A basal, *Trochammina-Buccella* biofacies (F3) extends from the sand layer at 69–71 cm depth to the base of the analyzed part of the core at 80 cm. This biofacies is characterized by a relatively diverse, shallow subtidal fauna, similar to that found in shallow embayments along the Pacific coast from Oregon to Alaska. *Buccella tennerima,* a conspicuous element of the fauna, lives mostly in sandy beach and tidepool sedi-

Table 1. *Diatoms from Catala Lake core 3*

Lithology Sample (cm)	Gyttja 0–1	Gyttja 11–13	Gyttja 17–19	Gyttja 23–25	Gyttja 27–29	Gyttja 31–33	Pl-det[1] 33–34.5	Gravel 34.5–39	Gyttja 39–41	Gyttja 43–45	Gyttja 47–49	Gyttja 51–53	Gyttja 55–57	Gyttja 59–61	Gyttja 63–65	Gyttja 67–69	Sand 69–71	Gyttja 71–73	Gyttja 73–75	Mud 78–80
Paralia sulcata	0.0	2.2	7.1	2.7	0.9	39.8	43.3	29.7	3.7	38.8	50.2	65.6	70.1	63.3	54.4	65.1	51.7	3.6	2.8	5.0
Cocconeis scutellum	0.0	5.0	14.1	23.1	9.9	8.1	9.8	2.7	1.4	9.0	2.9	7.1	3.3	8.7	22.1	14.5	12.0	6.5	3.7	13.9
Ophephora pacifica	0.0	0.0	0.8	1.6	0.0	0.4	0.0	0.0	0.0	2.5	2.1	0.4	0.0	0.0	0.4	2.0	10.3	25.9	57.7	31.6
Cocconeis costata	0.0	2.8	12.4	20.8	15.5	5.6	2.8	3.1	1.8	1.1	1.7	1.6	0.9	3.4	3.4	1.0	1.7	0.0	0.0	0.5
Other marine	0.0	3.1	4.1	7.5	3.0	4.6	9.3	3.9	0.5	4.7	6.3	5.5	6.6	8.7	6.1	8.6	7.9	1.6	3.3	3.5
All marine	0.0	13.0	38.6	55.7	29.3	58.5	65.1	39.4	7.4	56.1	63.2	80.2	80.9	84.1	86.3	91.1	83.5	37.7	67.4	54.4
Navicula aequora	0.0	0.0	2.5	0.8	0.4	0.0	0.5	3.1	22.1	13.3	4.2	3.2	0.5	0.0	0.0	1.0	1.2	0.0	0.0	2.5
Achnanthes hauckiana	0.0	1.6	2.9	7.1	0.4	1.4	0.5	3.1	14.7	12.6	3.8	1.6	0.5	0.5	0.4	0.3	0.0	0.4	0.0	1.0
Other marine-brackish	0.0	1.6	2.5	2.0	2.6	2.1	6.1	9.3	10.6	6.1	3.8	4.3	2.8	3.4	1.9	2.3	4.1	2.4	6.5	5.4
All marine brackish	0.0	3.1	7.9	9.8	3.4	3.5	7.0	15.4	47.5	32.0	11.7	9.1	3.8	3.8	2.3	3.6	5.4	2.8	6.5	8.9
Gyrosigma balticum	0.0	2.8	10.4	12.5	28.4	32.7	13.0	2.3	0.5	1.1	10.9	3.2	2.4	3.8	1.9	1.3	0.4	1.2	0.5	0.5
Other brackish	2.6	0.6	0.8	1.6	0.0	0.4	2.3	7.3	6.5	1.4	1.7	0.0	0.0	0.0	1.9	1.3	0.4	0.4	1.4	1.0
All brackish	2.6	3.4	11.2	14.1	28.4	33.1	15.3	9.7	6.9	2.5	12.6	3.2	2.4	3.8	3.8	2.6	0.8	1.6	1.9	1.5
Eunotia bidentula	34.5	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Eunotia sudetica	16.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fragilaria construens	11.2	71.7	14.9	18.8	14.7	3.2	5.1	27.4	20.7	3.2	2.9	3.6	2.8	5.8	6.5	1.0	8.7	56.7	23.3	29.4
Other fresh-brackish and fresh	35.1	8.4	26.6	1.6	24.1	1.8	7.4	8.1	17.1	6.1	9.6	4.0	9.3	2.4	1.1	1.6	1.7	0.8	0.9	4.0
All fresh-brackish and fresh	97.4	80.1	41.9	20.4	38.8	4.9	12.5	35.5	37.8	9.3	12.6	7.5	12.1	8.2	7.6	2.6	10.3	57.5	24.2	33.4
Unidentified/ unassigned	0.0	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.5	1.4	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.4	0.0	2.0
Number of valves	267	322	241	255	232	284	215	259	217	278	239	253	212	208	263	304	242	247	215	202
Number of taxa	27	26	38	26	23	22	22	35	32	33	31	27	24	19	20	28	23	16	17	29

[1] Plant detritus

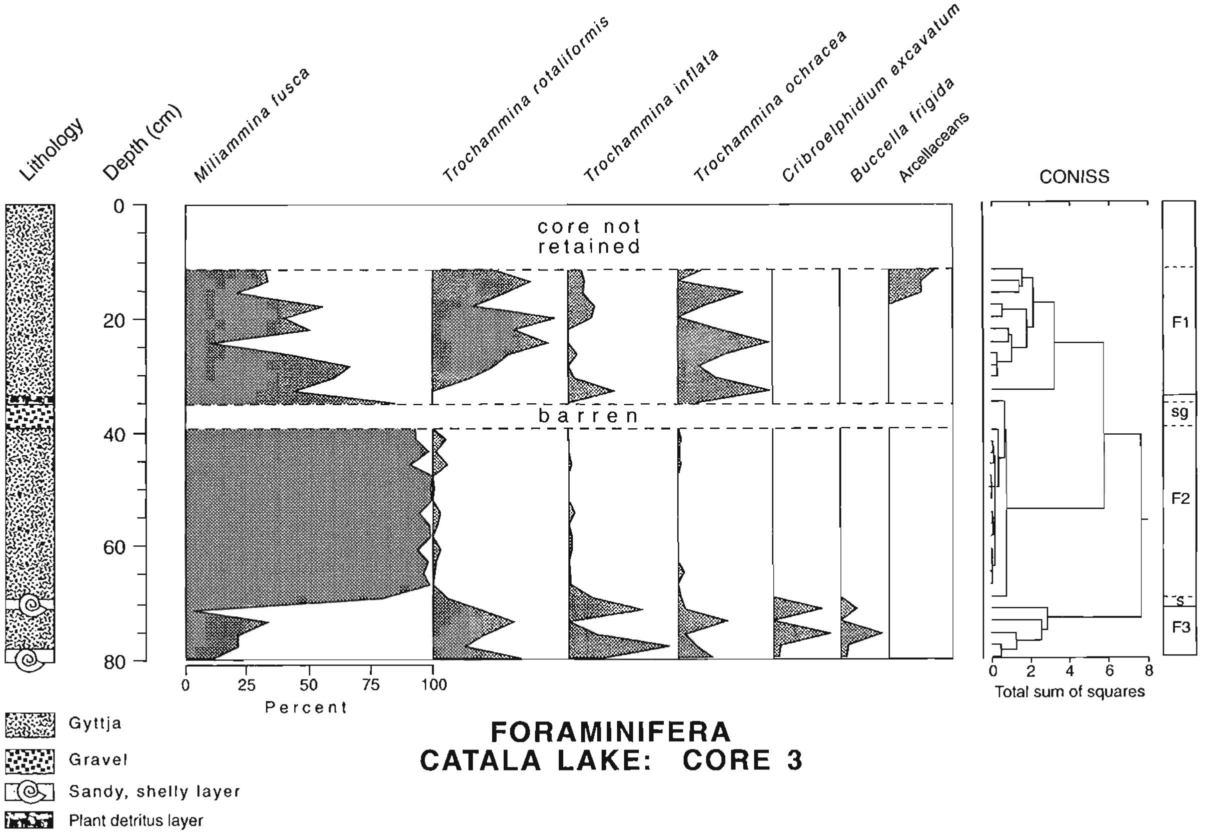

Figure 6. Foraminifera stratigraphy of the upper part of Catala Lake core 3, showing lithology, relative abundance of dominant taxa, results of the cluster analysis, and inferred foraminifera zones.

ments, and offshore at depths less than 12 m. The trochamminid species are also found mainly in shallow coastal waters, although *Trochammina inflata* is a mid- to high-marsh species and appears to be allochthonous in this biofacies.

Plant Macrofossils

A variety of plant and animal macrofossils was recovered from lake core 3 (Figures 7 and 8). Most of the plant remains occur near the top of, and just above, the gravel layer. Large (>0.5 cm) fragments of wood and bark, twigs (Figure 8a), and needles of spruce (*Picea*), hemlock (*Tsuga*), and red cedar (*Thuja*) are most abundant at these levels; and ericaceous (*Vaccinium*) seeds (Figure 8b) and sclerotia of a mycorrhizal soil fungus (*Cenococcum*; Figure 8c) were found only there. Well preserved fronds of three terrestrial mosses (*Antitrichia curtipendula, Eurhynchium praelongum,* and *Brachythecium* sp.) were recovered only from the sample directly above the gravel layer. *Antitrichia* (Figure 8d) is an epiphyte that typically festoons the branches and trunks of living trees, but also occurs on logs and rocks. *Eurhynchium praelongum* is a common species of coniferous forests and is found in a variety of habitats, including trees, logs, boulders, cliffs, and swamps. It also lives on seashores just above high tide level; in such a setting, it could easily be entrained by a tsunami and transported landward. Brackish conditions are indicated by the presence of fruits of the aquatic plant *Ruppia* (Figure 8e).

Animal remains include scattered fish bones, fragments of unidentified invertebrates, and elongated structures that are tentatively identified as colonial bryozoa (Figure 8f). These remains increase above the gravel layer and probably record a marine influence, since diatoms and foraminifera show a trend to increased salinity at the same levels.

CHRONOLOGY

Most of the cored sediments are less than 2,000 years old and thus late Holocene in age. Exceptions include the silty clay, gravel, and diamicton units (nos. 3–5), and possibly part of the organic-rich mud unit (no. 2), in some of the marsh cores. Five AMS ages on plant detritus capping the widespread sand-gravel sheet (sg) at 30–55 cm depth beneath Catala Lake range from 170 ± 40 to 580 ± 80 ^{14}C yr BP (Figure 3, Table 3). One additional age of 330 ± 60 ^{14}C yr BP was obtained on unidentified plant tissue recovered from a 2-mm-thick sand lamina about 10 cm above the gravelly layer in core 5. These ages are all maxima for the time of deposition of the sand and gravel (this assumes that the detritus layer and the subjacent sand and gravel were deposited during the same event, a reasonable assumption in view of the close as-

Table 2. *Arcellacea and foraminifera from Catala Lake core 3*

Lithology Sample (cm)	Gyttja 11–13	Gyttja 13–15	Gyttja 15–17	Gyttja 17–19	Gyttja 19–21	Gyttja 21–23	Gyttja 23–25	Gyttja 25–27	Gyttja 27–29	Gyttja 29–31	Gyttja 31–33	Pl-det 33–34.5	Gravel 34.5–39	Gyttja 39–41	Gyttja 41–43
Arcellacea															
Centropyxis aculeata	0	13	6	0	0	0	0	0	0	0	0	0	0	0	0
Difflugia oblonga	10	0	3	0	0	0	0	0	0	0	0	0	0	0	0
Difflugia urceolata	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Pontigulasia compressa	9	0	3	0	0	0	0	0	0	0	0	0	0	0	0
Foraminifera															
Ammonia beccarii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Buccella frigida	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Buccella tennerima	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cribroelphidium excavatum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidium crispum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Elphidiella hannai	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Haplophragmoides jeffreysei	0	7	3	6	0	0	5	4	0	7	0	6	0	0	0
Jadammina macrescens	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Lobatula fletcheri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lobatula mckannai	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Miliammina fusca	34	33	21	56	40	50	11	42	67	60	44	85	0	93	93
Spiroplectammina biformis	1	0	0	0	0	0	0	0	0	0	0	0	0	7	0
Trochammina inflata	6	7	6	11	10	0	0	4	0	3	19	0	0	0	0
Trochammina ochracea	12	0	27	11	0	17	37	19	8	15	38	8	0	0	2
Trochammina rotaliformis	26	40	30	17	50	33	47	31	25	15	0	0	0	0	5
Buliminella elegantissima	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Quinquelocula sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Number of tests	68	15	67	18	10	12	19	26	12	72	16	72	0	29	132
Number of species	8	5	9	5	3	3	4	5	3	5	3	4	0	2	3

[1] Plant detritus

sociation of the two). The range of radiocarbon ages (170–580 ^{14}C yr) is not surprising, because mixing of plant detritus differing in age by hundreds, even thousands, of years is common in many types of sediments, including tsunami deposits (CLAGUE and BOBROWSKY, 1994). The youngest of the detrital ages (170 ± 40 ^{14}C yr BP) can be taken as most closely approximating the age of the deposit. It corresponds to calendric ages of no more than 343 cal yr[1], suggesting that deposition occurred sometime after AD 1655.

Six AMS ages constrain the age of one or two older sand layers in the Catala Lake sequence. An AMS age of 1,000 ± 60 ^{14}C yr BP was obtained on a piece of bark or wood recovered from the top of the thin sand layer (ss) at site 13 along the Catala Lake marsh transect (Figure 4). Although thin, this sand layer is widespread in the marsh. It occurs at much greater depths than the sand-gravel sheet (sg) in the lake and thus appears to be older, a conclusion consistent with the above-mentioned radiocarbon age. A less likely possibility is that layers ss and sg correlate, in which case the dated wood from the marsh is much older than the sediment at the same level. The thin silt-sand layer in the marsh may correlate with the uppermost shelly layer in lake core 3, which gave AMS ages of 1,250 ± 50 ^{14}C yr BP on spruce and fir needles, 1,400 ± 60 ^{14}C yr BP on a twig, 1,690 ± 60 ^{14}C yr BP on a mussel fragment, and 2,080 ± 60 ^{14}C yr BP on a pelecypod valve (Figure 3, Table 3). The two shell ages, when corrected for the marine reservoir effect (SOUTHON *et al.*, 1990), are in general agreement with the needle and twig ages. These four ages, and another of 1,350 ± 70 ^{14}C yr BP on spruce needles and a cedar leaf from gyttja directly below the shelly layer, indicate that the shelly layer is no more than 1,400 cal yr old, and is probably less than 1,000 yr old, consistent with the age of layer ss in the marsh.

DISCUSSION

Relation of Lake and Marsh Stratigraphy

The upper portion of the Catala Lake sediment sequence, which consists largely of gyttja, correlates with unit 1 (peat) and part of unit 2 (organic-rich mud) in the marsh (Figure 9). The lower part of the sediment sequence in the lake, comprising interbedded gyttja, organic-rich mud, silt, and sand, correlates with the lower part of marsh unit 2. Radiocarbon

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[1] Calibrated (approximately calendric) years before AD 1998 (see Table 3).

Table 2. *Extended.*

Gyttja 43–45	Gyttja 45–47	Gyttja 47–49	Gyttja 49–51	Gyttja 51–53	Gyttja 53–55	Gyttja 55–57	Gyttja 57–59	Gyttja 59–61	Gyttja 61–63	Gyttja 63–65	Gyttja 65–67	Gyttja 67–69	Sand 69–71	Gyttja 71–73	Gyttja 73–75	Gyttja 75–78	Mud 78–80
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	3
0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	17	3	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	6
0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	23	3	3
0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0
1	0	0	0	0	0	0	0	1	1	1	0	2	7	7	1	7	8
0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	90	100	99	99	94	98	99	94	98	96	99	79	3	36	21	21	11
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	2	0	1	1	0	0	1	10	30	0	11	40	14
1	1	0	0	1	1	0	0	1	0	2	0	1	3	21	3	7	14
1	6	0	1	0	3	2	0	3	1	0	0	6	20	36	21	13	37
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
162	84	67	283	152	165	649	170	444	334	217	410	164	30	14	141	67	35
4	5	1	3	2	4	3	2	5	5	5	4	6	10	4	10	10	9

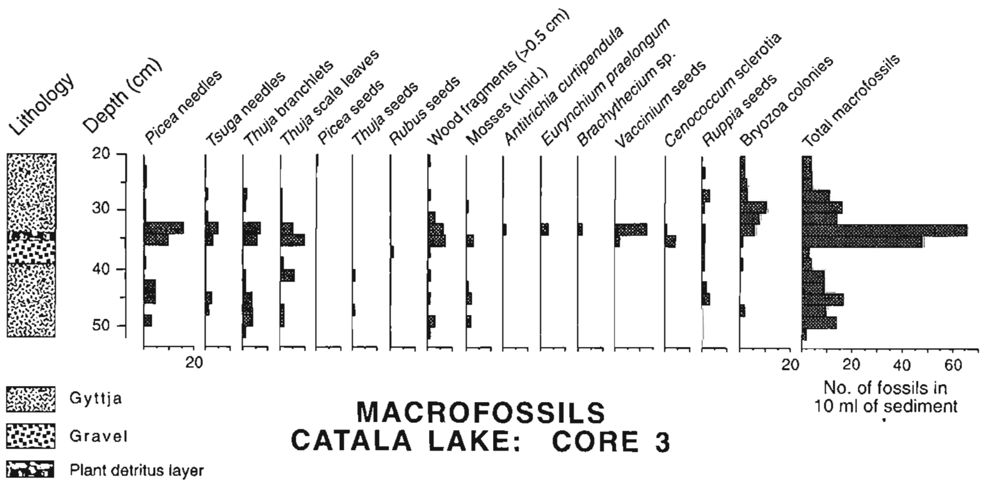

Figure 7. Distribution of plant fossils (> 250 μm) in Catala Lake core 3 (20–52 cm depth).

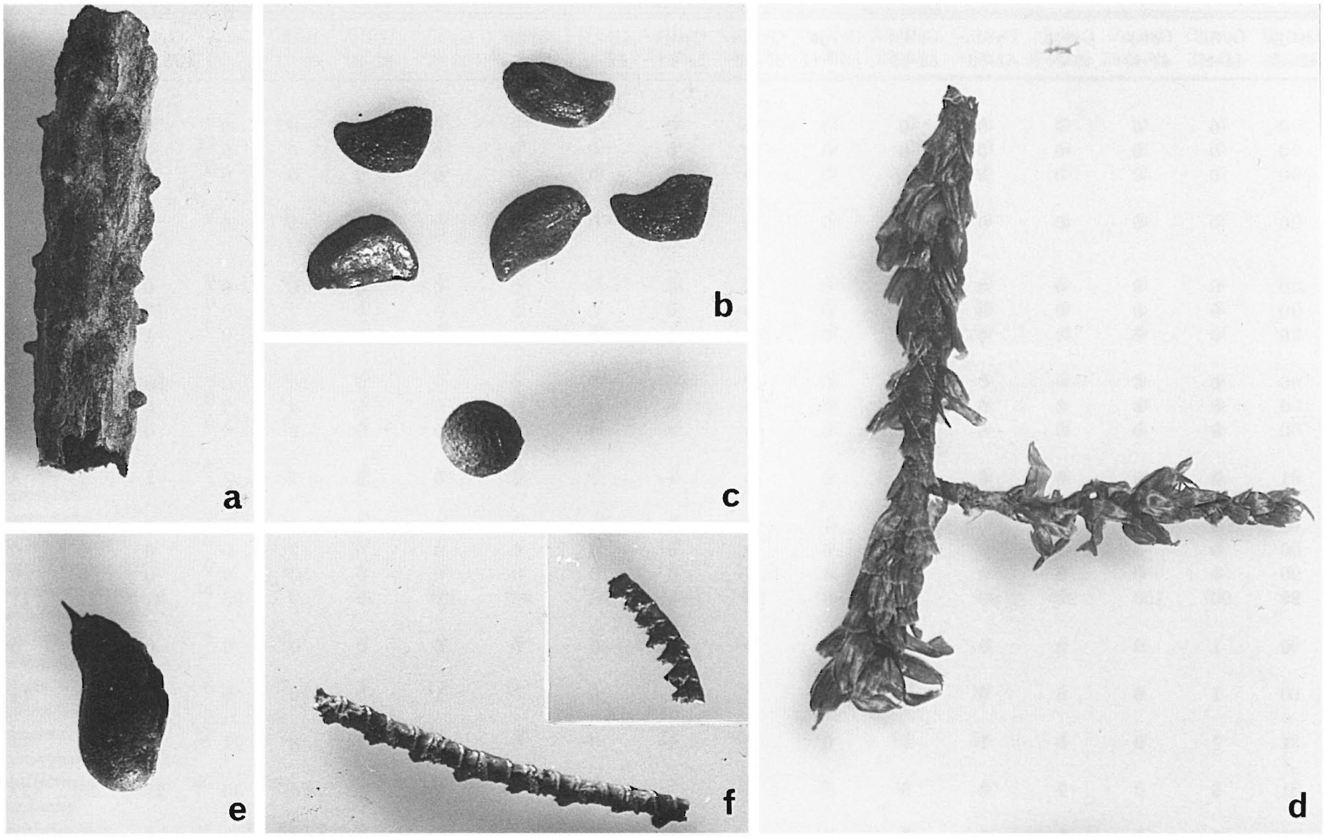

Figure 8. Selected plant fossils from Catala Lake core 3. All specimens are from the upper part of the gravel layer and the overlying plant detritus (32–36 cm depth). (a) *Picea* twig with characteristic woody pegs where needles were attached (7 ×). (b) Five seeds of *Vaccinium,* a berry-producing forest shrub (10 ×). (c) Spheroidal sclerotium of the soil fungus *Cenococcum* (10 ×). (d) Stem and branch fragment of the epiphytic moss *Antitrichia curtipendula* (5 ×). (e) Fruit of *Ruppia,* a submerged brackish-water aquatic plant (10 ×). (f) Two fragments of suspected bryozoan colonies (10 ×). *Vaccinium, Cenococcum,* and *Antitrichia curtipendula* were found only in the gravel layer.

Table 3. *Radiocarbon ages from Catala Lake.*

Radiocarbon Age (^{14}C yr BP)[a]	Calibrated Age Range (cal yr before AD 1998)[b]	Laboratory No.[c]	Core No. (Figs. 3, 4)	Depth (cm)[d]	Dated Material
170 ± 40	0–343	TO-5420	3	34	Twig
330 ± 50	334–555	TO-5958	5	40	Twig
330 ± 60	0–558	TO-5957	5	32	Plant tissue
420 ± 50	363–583	TO-5959	5	40	Bark
460 ± 80	356–672	TO-5891	3	34	Twig
500 ± 70	380–694	TO-6546	5	57	Bark
580 ± 80	549–717	TO-5890	3	34	*Picea* needles
1,000 ± 60	790–1099	TO-5318	13	84	Bark or wood fragment
1,250 ± 100	1000–1389	TO-6544	3	69	*Picea* and *Tsuga* needles
1,350 ± 70	1133–1433	TO-6229	3	71	*Picea* needles, *Thuja* leaf
1,400 ± 60	1228–1455	TO-5893	3	69	Twig
1,690 ± 60	736–1017[e]	TO-6545	3	69	*Mytilus* fragment
2,080 ± 60	1146–1406[e]	TO-5892	3	70	Pelecypod valve

[a] Laboratory-reported error terms are 1 σ. Ages are normalized to $\delta^{13}C = -25.0‰$ PDB

[b] Determined from dendrocalibrated data of STUIVER and BECKER (1993) and STUIVER and BRAZIUNAS (1993). The range represents the 95% confidence interval (±2σ) calculated with an error multiplier of 1.0 (note: error multipliers expand laboratory-quoted errors to cover uncertainties in reproducibility and systematic bias; for a discussion, see STUIVER and PEARSON, 1993)

[c] TO, IsoTrace Laboratory (University of Toronto)

[d] Depth below lake floor or marsh surface

[e] Incorporates a reservoir correction of 790 ± 35 years (SOUTHON *et al.,* 1990)

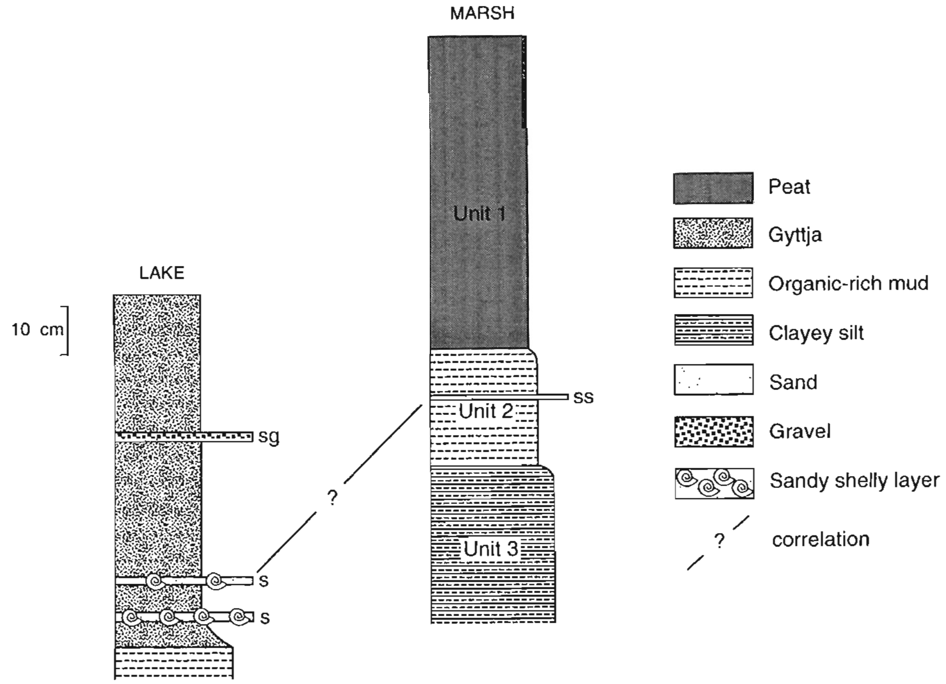

Figure 9. Generalized lake and marsh stratigraphies, showing a correlation between the uppermost sandy shelly layer in the lake and layer ss in the marsh.

ages suggest that the conspicuous sand and gravel layer (sg) in the lake has no counterpart in the marsh. Likewise, sandy shelly layers (s) in the lower part of the lake sequence do not occur in the marsh, although layer ss in the marsh is possibly a distal equivalent of the uppermost of these layers. The basal gravel and diamicton units (nos. 4 and 5) in the marsh have no counterparts in the lake, and probably predate the oldest sediments in the lake cores.

Environmental Changes

Microfossil data show that Catala Lake was a low-energy tidal lagoon throughout most of period recorded by the cores, that is the last 2,000 years. Although marine and brackish diatoms were not found in samples of surface sediment in the lake, they, along with foraminifera, are present near the top of core 3 (Figures 5 and 6). The recent change from brackish lagoon to freshwater lake may be due to gradual uplift. Tide gauge records and releveling survey data show that the central west coast of Vancouver Island is rising at rates of several millimeters per year (RIDDIHOUGH, 1982; HYNDMAN and WANG, 1995), and average emergence of about one millimeter per year over the past several thousand years has been documented from geologic data (CLAGUE *et al.*, 1982; FRIELE and HUTCHINSON, 1993).

The most pronounced changes in diatom and foraminifera assemblages in core 3 coincide with deposition of the gravel layer at 35–37 cm depth and the sand layer 32 cm lower (Figures 5 and 6, Tables 1 and 2). These layers have distinctive diatom assemblages, characterized by abundant marine shoreface and brackish species (Figure 5). Marine diatoms increase, relative to fresh and fresh-brackish taxa, after the deposition of each coarse layer (Figure 5). Thus, whereas only 7% of the diatoms in the sample directly below the upper coarse layer are marine, the sample immediately above this layer contains 60% marine species (Table 1). Values for samples below and above the lower coarse layer are 38% and 91%, respectively. Changes in foraminifera assemblages are equally dramatic, although not as easily interpreted. Samples above the upper coarse layer have more diverse assemblages than the sample directly below it (Figure 6, Table 2). This change in faunal diversity likely reflects a return to more saline conditions after deposition of the upper coarse layer. Most of the samples between the two coarse layers have low-diversity faunas (Figure 6), but specimen counts are relatively high. Higher diversity assemblages and/or low total counts characterize most samples below the lower coarse layer.

The diatom and foraminiferal data provide evidence for long-lasting changes in the environment of Catala lagoon when the upper two coarse layers were deposited. We suggest two explanations for the change to relatively more saline conditions immediately after the deposition of each coarse layer. First, strong waves may have deepened the tidal channel connecting the lagoon to the sea, or they may have eroded the gravel bar at the mouth of the lagoon. PLAFKER and KACHADOORIAN (1969) noted that the barrier beaches of several coastal lakes were breached by tsunamis associated with the great 1964 Alaska earthquake. Similar breaching at Catala Island would increase tidal exchange and make the lagoon more saline. Second, this part of Vancouver Island may have subsided during large earthquakes at the time the two coarse layers were deposited. Even a small amount (a decimeter or two) of coseismic subsidence would be sufficient to produce the observed changes in microfossil assemblages in Catala Lake.

The diatom and foraminifera data also provide evidence for freshening of the lagoon immediately before deposition of the two coarse layers. The sample directly below each coarse layer contains a much higher percentage of fresh and fresh-brackish diatoms than those lower in the sequence (Table 1). The same samples also have much more limited foraminifera faunas than lower samples (Table 2). The reason for this apparent freshening is uncertain, but one possibility is that relative sea level fell (*i.e.,* the land rose) during periods before large earthquakes. Compression and shortening of the crust above a locked subduction zone during interseismic intervals (DRAGERT *et al.,* 1994; HYNDMAN and WANG, 1995) would produce such an uplift, although it should not be limited to times immediately before the earthquakes. Another possible explanation for the apparent freshening is that marshes expanded at the shores of the lagoon during the interseismic period before each earthquake and, thus, contributed increasing amounts of fresh and fresh-brackish diatoms to sediments accumulating in the basin.

The plant detritus within, and directly above, the upper coarse layer in cores near the outlet of Catala Lake records inwash of soil material. This material was eroded from the forest bordering the outlet stream by incoming waves.

Origin of Coarse Sediment Layers

The uppermost sheet of coarse sediment (sg) at Catala Lake thins and fines landward away from the lake outlet, consistent with deposition by a tsunami. The thin sheet of silt and sand (ss) beneath the marsh also thins inland away from the lake shore, pinching out in the upper part of the marsh. Processes other than tsunamis do not adequately explain these spatial trends. Stream floods, for example, would not produce thin sheets of sand and gravel that become finer away from the outlet and shore of Catala Lake. Furthermore, no streams capable of depositing sand and gravel enter Catala Lake.

In open coastal settings, the deposits of rare large storms are commonly difficult to distinguish from tsunami deposits (FOSTER *et al.,* 1991). DAWSON *et al.* (1988, 1991), however, suggested that tsunami waves typically spread sediment widely above the upper limit of tides, whereas storm waves are less likely to move sediment far inland. Storm deposits are unlikely to be found far inland of the coast in protected inlets and lagoons because, as water levels rise, current velocities in channels drop below values required to transport enough sand to form widespread sheets (BOURGEOIS and REINHART, 1989; PETERSON and DARIENZO, 1996). Catala Lake lies in a very protected setting 500 m from the coast. It is sheltered from the sea by high ground on all sides, except near the narrow, ephemeral outlet stream. The outlet stream flows into a protected bay and is itself bordered by dense forest.

Some of the paleoenvironmental evidence, presented above, suggests that tsunamis are more likely than storms to have left the coarse sediment layers in Catala Lake. Sudden, lengthy increases in salinity, indicated by the diatom and foraminifera data, coincide with deposition of the upper two coarse layers in the lake. As suggested above, one explanation for the salinity increases is coseismic subsidence. Earthquakes responsible for the subsidence would have triggered tsunamis that deposited sand and gravel in the lake.

A less direct argument for a tsunami origin for the uppermost coarse sediment sheet at Catala Lake is that its age is similar to that of the last great Cascadia earthquake, which left a sheet of sand and gravel in many tidal marshes on Vancouver Island (CLAGUE and BOBROWSKY, 1994; BENSON *et al.,* 1997). As mentioned previously, this earthquake occurred in AD 1700. Radiocarbon dating reported in this paper shows that the widespread sheet of sand and gravel in Catala Lake was deposited after AD 1655 (Table 3).

The age of the marsh silt-sand sheet may be the same as that of another earthquake at the Cascadia subduction zone. The penultimate great Cascadia earthquake has been dated at 1000–1100 cal years on the southwest Washington coast (ATWATER and HEMPHILL-HALEY, 1997), and the silt-sand layer in the Catala marsh was deposited no more than 1,050 cal years ago (Table 3). However, we interpret the single radiocarbon age from the marsh with caution; the silt-sand layer could be younger than 1,050 cal years, in which case these two events are unrelated. Whatever its age, the layer was probably deposited by a tsunami, because it thins landward and has a sheet-like geometry. A great storm could possibly produce such a deposit, but such a storm would have had to have been the largest of the last 1,000 years, as no other younger layers of silt or sand are present in the marsh.

Some of the other coarse beds in the Catala Lake cores may also be tsunami deposits. We do not, however, have enough information about the distribution, form, internal structure, and particle-size distribution of these beds to test this hypothesis. Also, our ability to accurately reconstruct the paleogeography of the Catala Lake basin, which is important in interpreting the sediments, is poorer for events older than about 1,000 years.

Tsunami Hazard

Work at Catala Lake and elsewhere on Vancouver Island (CLAGUE and BOBROWSKY, 1994; BENSON *et al.,* 1997; HUTCHINSON *et al.,* 1997) has provided valuable information on the tsunami hazard on the Pacific coast of Canada. Large tsunamis generated by great Cascadia earthquakes entered low-lying lakes and tidal marshes on Vancouver Island, leaving distinctive layers of sand and gravel. The tsunamis are recorded, not only on the outer coast of the island, but also at the heads of fiords that deeply indent it. Observations during the 1964 Alaska tsunami indicate that wave heights and run-up were greater at many fiord heads than on the outer coast, and this is also likely to have been the case for prehistoric tsunamis of great Cascadia earthquakes.

We have not attempted to estimate tsunami size from our field data, but we note that the tsunami of the most recent

Cascadia earthquake, likely one of the largest in the last several thousand years (SATAKE *et al.*, 1996), did not enter some lakes on the outer coast of Vancouver Island that are only a few meters above the upper limit of tides. This tsunami reached Catala Lake, which is less than 1 m above high tide level, but apparently was not vigorous enough to deposit sediment in the marsh bordering the lake. Tsunamis, however, vary tremendously in size over short distances, largely due to differences in the orientation and shape of the shoreline and the slope of the seafloor seaward of the site. Thus, for example, one would not expect tsunami run-up at Catala Island, which is a small isolated island flanked by a narrow, shallow-water platform, to be as great as run-up at the heads of many inlets, where resonance would cause amplification of incoming waves. In general, however, our work suggests that past Cascadia tsunamis were not as large as suggested by some researchers who have simulated the tsunamis using numerical models. Wave amplitudes of about 5 m on the outer coast of Vancouver Island, and as much as 15 m at the heads of some inlets, have been predicted by some modelers (NG *et al.*, 1990, 1991). On the basis of our data, however, we consider that waves on most of the outer coast were probably less than 5 m high. Such waves, nevertheless, pose a significant hazard to western Vancouver Island. Some sense of the degree of this hazard is given by the fact that the 1964 Alaska tsunami, which was probably smaller than most Cascadia tsunamis by the time it reached British Columbia, caused over $10M damage (1964 Cdn. dollars) on Vancouver Island (THOMSON, 1981).

CONCLUSION

Two or more tsunamis triggered by prehistoric earthquakes are probably recorded in sediments at Catala Lake off the west coast of Vancouver Island. The deposits are thin sheets of silt, sand, and gravel in an otherwise fine sequence of organic-rich sediments. A sheet of coarse sediment beneath the floor of Catala Lake thins and fines away from the outlet; another sheet of sand and silt beneath the bordering marsh thins inland away from the lake shore. These trends are consistent with deposition by landward-surges of water during tsunamis or great storms. Deposition of two coarse layers coincided with marked changes in diatom and foraminifera communities within the low-energy lagoon that was the precursor to Catala Lake. Notably, the lagoon freshened immediately before, and became more saline after, each layer was deposited. These environmental changes were probably caused by erosion of the lake outlet by tsunamis or by preseismic and coseismic land-changes. Radiocarbon dating shows that the youngest sheet of coarse sediment at Catala Lake was deposited sometime after the mid-1600s; we attribute it to the tsunami of the last great earthquake at the Cascadia subduction zone in AD 1700. The tsunami of the penultimate great Cascadia earthquake, which occurred 1,000–1,100 years ago, may be recorded by an older layer of coarse sediment at Catala Lake.

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