

FORAMINIFERAL EVIDENCE FOR THE AMOUNT OF COSEISMIC SUBSIDENCE DURING A LATE HOLOCENE EARTHQUAKE ON VANCOUVER ISLAND, WEST COAST OF CANADA

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Abstract — Foraminiferal data from two sites, 6 km apart, on the shores of an inlet near Tofino on the west coast of Vancouver Island, British Columbia, allow estimates to be made of the amount of coseismic subsidence during a large earthquake 100–400 years ago. The sampled sediment succession at the two sites is similar; peat representing a former marsh surface is abruptly overlain by intertidal mud grading upward into peat of the present marsh. At one of the sites, a layer of sand, interpreted to be a tsunami deposit, locally separates the buried peat from the overlying intertidal mud. The abrupt peat-mud contact records sudden crustal subsidence during the earthquake. The paleoelevation of each fossil sample was estimated by comparing its foraminiferal assemblage with modern assemblages of known elevation. The modern assemblages were obtained from surface samples collected along transects across the marsh near the fossil sample sites. Comparisons were made statistically using transfer functions. Estimates of coseismic subsidence, based on differences in paleoelevations just above and below the top of the buried peat, range from 20 cm to 1 m, with the most likely value in the 55–70 cm range. Post-seismic crustal rebound began soon after the earthquake and may have been largely complete a few decades later. Copyright © 1996 Published by Elsevier Science Ltd



INTRODUCTION

Foraminiferal data presented in this paper are used to estimate the amount of subsidence that accompanied a large earthquake on western Vancouver Island, British Columbia, less than 400 years ago. This study builds on, and refines, the previous study of Guilbault *et al.* (1995) in the same area. The work is founded on the principle that foraminiferal assemblages in tidal marshes vary with elevation and that a change in elevation of as little as 5–10 cm may produce a recognizable change in the foraminiferal assemblage at a given site. This is the essence of the conclusions of Scott and Medioli (1980), based on their investigation of Nova Scotia tidal marshes. This paper and others concerned more specifically with marsh foraminifera from the northwest coast of North America (Phleger, 1967; Williams, 1989; Patterson, 1990a; Jennings and Nelson, 1992; Jonasson and Patterson, 1992) and from Chile (Jennings *et al.*, 1995), provide a basis for discriminating upper marsh from lower marsh environments on the British Columbia coast. Broad limits can then be placed on paleoelevations of samples from intertidal sedimentary sequences using foraminiferal data (Jennings and Nelson, 1992), provided

the vertical limits of the marsh zones are known and have not changed with time.

The originality of our method lies in the use of transfer functions to estimate paleoelevation (Imbrie and Kipp, 1971). This approach allows a more objective treatment of foraminiferal assemblages than is possible through visual inspection and can be applied to large, multivariate data sets. It also provides a paleoelevation for every sample in a sequence, thus improving the resolution.

In this paper, we compare fossil foraminiferal assemblages at two sites, 6 km apart, near Tofino, British Columbia, with modern assemblages from the adjacent marsh. At both sites, a peat layer representing a former marsh is abruptly overlain by mud that grades upward into peat of the present marsh. The abrupt change from peat to mud has been attributed to sudden subsidence during a large earthquake 100–400 years ago (Clague and Bobrowsky, 1994a). The earthquake may have resulted from the rupture of the boundary between the North America and Juan de Fuca plates along the Cascadia subduction zone (Fig. 1). Samples collected through the sediment sequence at each site were compared with samples taken from a nearby modern transect no more than 150 m away. This was done to minimize the

environmental differences between the fossil and modern sites, which could affect comparison of the data sets.

By assigning a paleoelevation to each fossil sample, we obtain an elevational history of the site, from which local submergence or emergence during an earthquake can be inferred. The instantaneous nature of earthquake subsidence or uplift eliminates complicating factors such as eustatic and isostatic sea level change, sediment accretion, slow tectonic movements, and long-term sediment compaction. The amount of sudden submergence or emergence determined from foraminiferal data, however, may differ from the amount of subsidence or uplift caused by the earthquake (Guilbault *et al.*, 1995). Possible sources of error include a change in tidal range due to a change in the shape of the basin during the earthquake, coseismic sediment compaction, the presence of an

erosional hiatus in the succession of analyzed sediments, and early post-seismic rebound before sediment begins to accumulate on coseismically subsided surfaces. We will come back to these points in the discussion.

STUDY SITES

The two sampled sites are marshes adjacent to Browning Passage, an arm of the sea connecting the open ocean southwest of Tofino with fjords and channels farther inland (Fig. 1). Tidal marshes along Browning Passage are low-energy environments sheltered from the open Pacific Ocean by Esowista Peninsula and by numerous islands north and west of Tofino.

The 'cemetery' site (Guilbault *et al.*, 1995; site 4 of

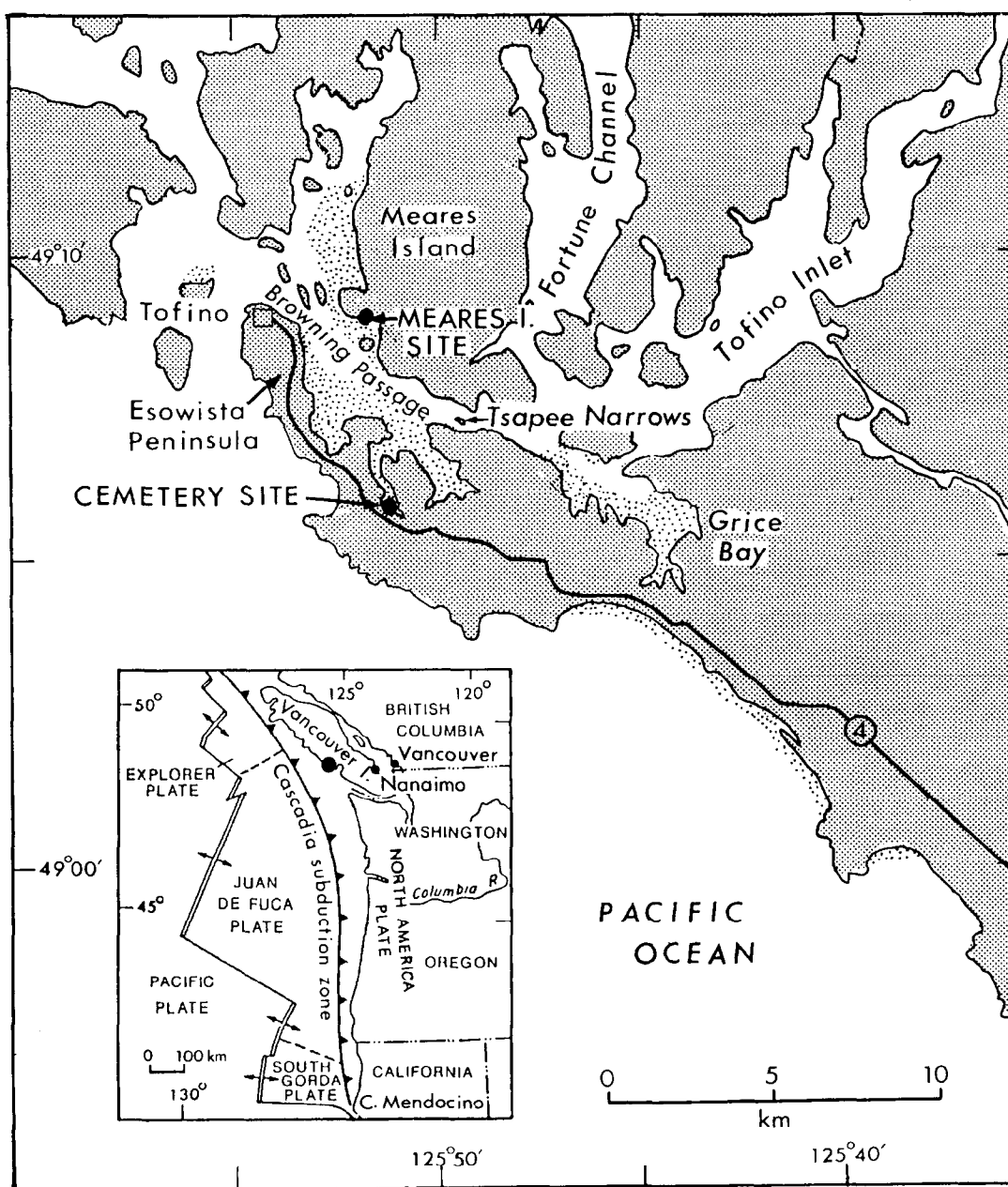
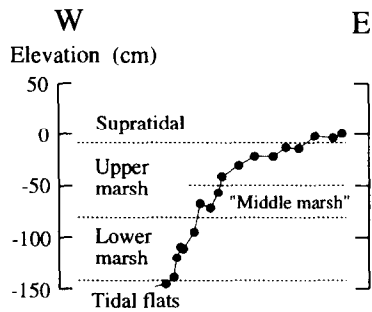


FIG. 1. Map of the Tofino area showing the locations of the cemetery and Meares Island sections. Stippled areas are intertidal. Inset map shows lithospheric plates; dot indicates the location of the detailed map.

(a) Cemetery transect



(b) Meares Island transect

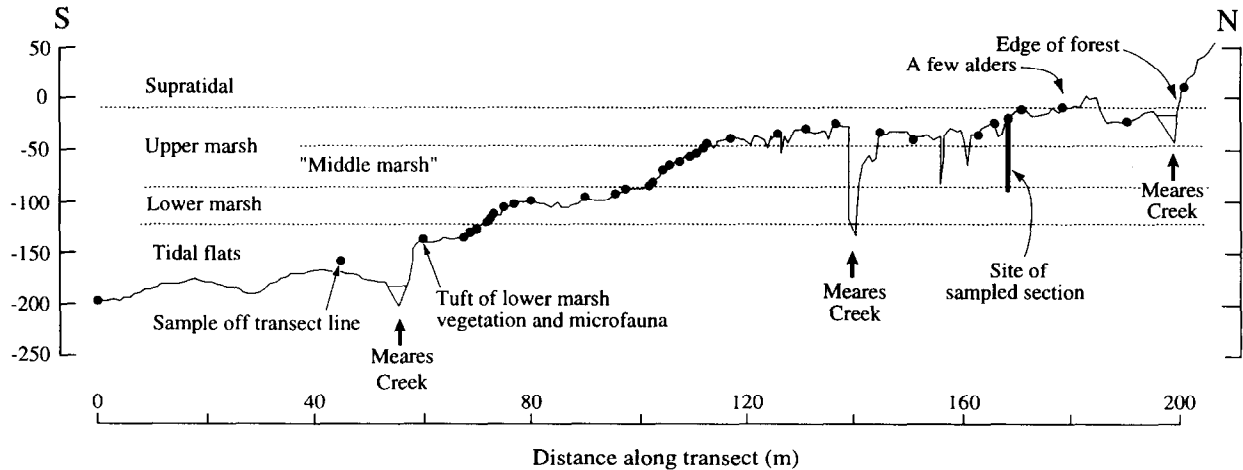


FIG. 2. Profiles of the two sampled marshes. Dots represent modern samples.

Clague and Bobrowsky, 1994a) is located 7 km south-southeast of Tofino, near the head of a long, narrow, shallow, winding arm of Browning Passage. This site is completely protected from wave action and is fringed by a narrow marsh. Samples of surface sediment for the modern data base were collected along a 32-m-long transect across the marsh (Fig. 2(a)). The site was chosen because it is close to the fossil section and because the marsh is broader here than elsewhere in the immediate vicinity; consequently, the different foraminiferal biofacies were expected to be better developed and more complete.

The succession of late Holocene sediments underlying the marsh was sampled in the wall of a tidal channel located approximately 100 m east-southeast of the modern transect. The following lithostratigraphic units are exposed in the section (Fig. 3):

Unit 5 (0–3 cm below the marsh surface): dark brown, rooty, muddy peat of the modern tidal marsh; grades downward into unit 4.

Unit 4 (3–27 cm): olive-gray, organic-rich mud, becoming lighter and less peaty downward; the contact between this unit and the underlying muddy peat (unit 3) is abrupt.

Unit 3 (27–31 cm): dusky brown, rooty, muddy peat (a former marsh surface) with a gradational lower contact.

Unit 2 (31–53 cm): olive-gray, organic-rich mud similar to unit 4; the uppermost several centimeters are darker and richer in plant material than the rest of the unit; grades downward into unit 1.

Unit 1 (53–75 cm): interstratified, olive-gray mud and sandy silt, becoming sandier downward; the uppermost 6 cm of the unit were sampled.

Unit 1 rests on late Pleistocene, glaciomarine, silty clay containing shells dated at about 16 000 years BP (calibrated age; Clague and Bobrowsky, 1994a). Large conifer stumps rooted in this clay or in the sediments that directly overlie it have been dated at about 7400 to 9000 years BP (Clague and Bobrowsky, 1994a). The five units described above overlie these fossil forest remains. Accelerator mass spectrometry (AMS) radiocarbon ages on *Triglochin* rhizomes from the cemetery section indicate that unit 2 is no more than 700 years old (Table 1).

The second study site (near site 1 of Clague and Bobrowsky, 1994a) is situated on Meares Island, 3 km east of Tofino and 6 km north of the cemetery site. It lies at the head of a broad bay that opens to the southwest onto Browning Passage. The tidal marsh is much broader here than at the cemetery site; the lower part is patchy and irregular, perhaps due to greater exposure to waves. Samples of surface sediment were collected along a 128-m-long transect from the forest edge to the unvegetated tidal flats (Fig. 2(b)). To maximize the comparability of the modern and fossil records, the fossil site was located along the transect; the uppermost sample at the fossil site is one of the modern samples of the transect. The transect crosses Meares Creek at three places (Fig. 2(b)); freshwater acellacea are carried into the marsh at these points.

Fossil samples were collected from the wall of a pit that

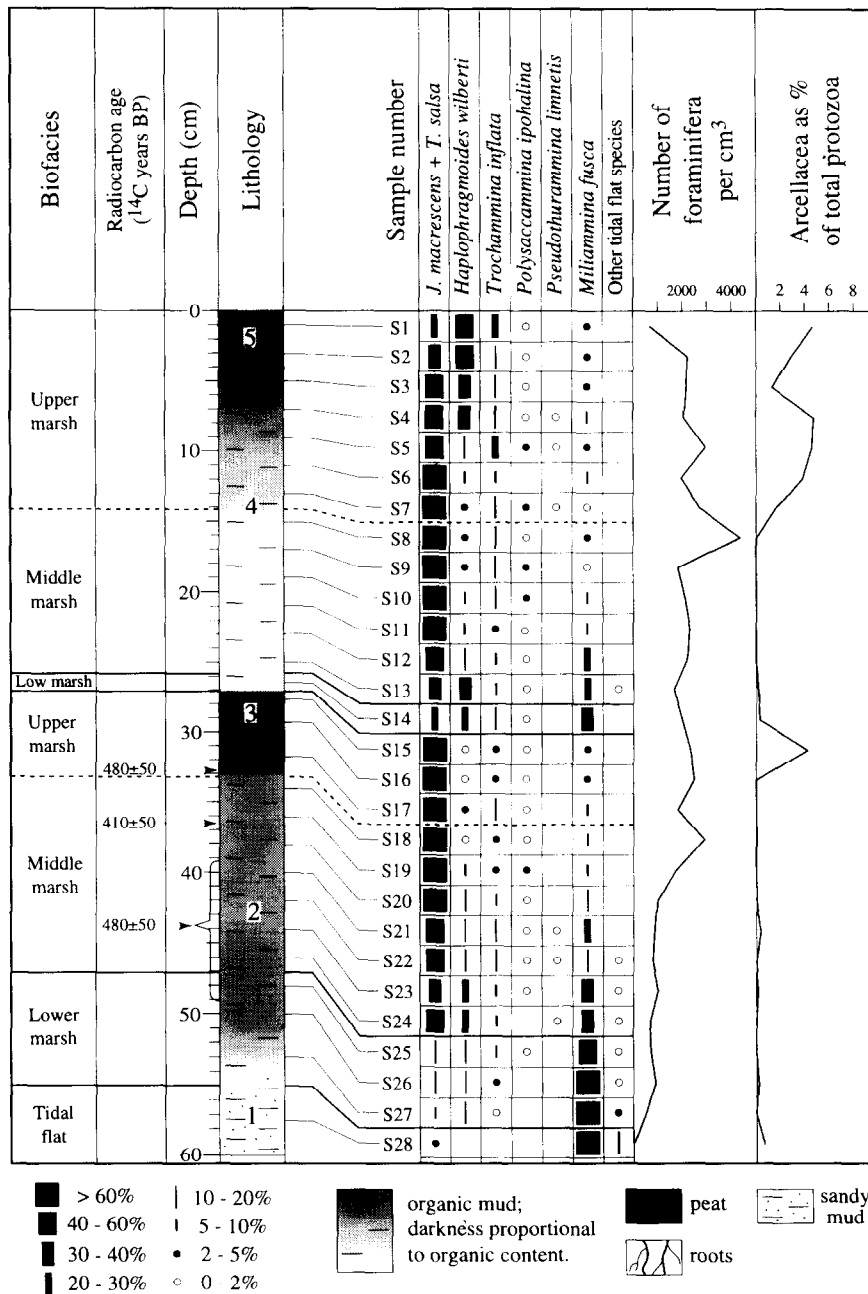


FIG. 3. Lithostratigraphy, radiocarbon ages and distribution of major foraminiferal taxa in the cemetery section. Percentages were computed on the sum of determined foraminifera only; percentages of arcellacea in the protozoa total are shown at the right. Numbered lithologic units are described in the text. Low marsh and tidal flat species other than *Miliammina fusca* (*Ammobaculites exiguus*, *Ammotium salsum* and *Polysaccamina hyperhalina*) have been grouped. *Miliammina fusca* percentages have been corrected for the 'M. fusca factor' of Guilbault *et al.* (1995). The middle marsh is a subfacies of the upper marsh, hence the dashed boundary.

was dug in the upper part of the marsh. The following succession of stratigraphic units was recorded at this site (Fig. 4):

Unit 8 (0–4 cm below the marsh surface): dark brown, rooty, muddy peat of the present marsh; the contact with unit 7 is sharp.

Unit 7 (4–4.5 cm): silty mud (possibly a tsunami deposit; see Clague and Bobrowsky, 1994a, b); sharp lower contact.

Unit 6 (4.5–18 cm): brown muddy peat, upper part rooty, becoming muddier with depth; gradational lower contact.

Unit 5 (18–28 cm): olive gray, organic-rich mud; sharp lower contact.

Unit 4 (28–34 cm): fine sand (tsunami deposit; Clague and Bobrowsky, 1994a, b); sharp lower contact.

Unit 3 (34–39 cm): brown, rooty, muddy peat (former marsh surface); gradational lower contact.

Unit 2 (39–69 cm): olive gray, organic-rich mud similar to unit 5; sharp lower contact.

Unit 1 (69–83 cm): poorly sorted, gravelly sand grading downward into sandy gravel.

Unit 1 is a lag developed on late Pleistocene glaciomarine sediments (Clague and Bobrowsky,

TABLE 1. Radiocarbon ages from the two Tofino study sites

Radiocarbon age (¹⁴ C years BP) ^a	δ ¹³ C (‰)	Calibrated age range (cal years before AD 1950) ^b	Laboratory number ^c	Stratigraphic unit ^d	Dated material
Cemetery site					
480±50		300–650	TO-4054	2	<i>Triglochin</i> rhizome ^e
410±50		0–630	TO-4055	2	<i>Triglochin</i> rhizome ^e
480±50		300–650	TO-3522	2	<i>Triglochin</i> rhizomes ^e
Meares Island					
180±50		0–470	TO-3518	3	Conifer needles, cedar scales
340±50		0–540	TO-3517	4	Branch
440±60		0–650	TO-3519	3	Rhizomes, leaves ^e
630±50		500–730	TO-3520	2	Conifer cone
680±50		510–780	TO-3521	2	Twig
700±60	–24.9	550–720	GSC-5522	2	Branch ^f
1140±50		800–1280	TO-3516	3	Conifer cone

^aLaboratory-reported error terms are 2σ for GSC age and 1σ for all others. Ages corrected to δ¹³C = –25.0‰ PDB.

^bDetermined from dendro-calibrated data of Stuiver and Pearson (1993). The range represents the 95% confidence interval based on the 2σ error limits of the radiocarbon age (error multiplier=2.0; note: error multipliers expand laboratory-quoted errors to cover uncertainties in reproducibility and systematic bias; for a discussion, see Stuiver and Pearson, 1993).

^cGSC=Geological Survey of Canada; TO=IsoTrace (University of Toronto).

^dSee text and Figs 3 and 4.

^eIn growth position.

^f*Picea* sp. (identified by H. Jetté, GSC Wood Identification Report 93.10).

1994a). A branch lying at the top of unit 1 gave a calibrated radiocarbon age of 550–720 years BP (Table 1). Rhizomes in growth position just below unit 4 (tsunami sand) are less than 700 years old, and detrital wood and other plant material from within and just below this sand are no more than 600 years old. The sand has been optically dated at 325±25 years old (Huntley and Clague, 1996). The section as a whole is thus young, probably spanning no more than 1000 years.

The buried peat at the cemetery and Meares Island sites represents a former marsh that subsided suddenly during a large earthquake (Clague and Bobrowsky, 1994a). At Meares Island and at many other places along Browning Passage, the buried peat is overlain by sand that was deposited by the tsunami generated by the earthquake. The sand is not present, however, in the cemetery section. At some sites along Browning Passage, the tsunami apparently eroded the subsided marsh (Clague and Bobrowsky, 1994b), but this probably did not happen at the cemetery site, nor for that matter at Meares Island where delicate stems and leaves of herbaceous plants extend upward from the buried peat into the overlying sand.

Tides

The predicted level of the highest tide at the tidal gauge at Tofino harbour for the summer of 1994 (July, August,

and September) is 3.7 m (Fisheries and Oceans, 1993). The recorded high tide at Tofino harbour on July 14, 1994, when we sampled the Meares Island transect, was 3.18 m. The recorded high tide on June 24, 1993, when we sampled the cemetery transect, was 3.21 m. We surveyed the level reached by high tide at the cemetery and Meares Island sites on these two days. We also estimated the height of the highest tide at the two sites during the summer of 1994 by assuming that the amplitude of tides are the same at the transects as at the Tofino gauge (Table 2). There is no proof, however, that tidal amplitude is the same at the three localities. Table 2 includes the height of an 'exceptional' tide; an exceptional tide is here defined as the level reached by the sea no more than 0.1% of the time. At Tofino harbour, this level is based on 18 years of tidal data collected from 1977 to 1994 inclusively (unpublished data from Fisheries and Oceans Canada).

METHODS

Modern samples (0–2 cm depth) were collected with a garden bulb planter. Eighteen samples (20 if the top of the section and one forest soil sample are included) were collected over a 1.45 m vertical range along the cemetery transect. Vertical intervals between these samples range

TABLE 2. Estimated maximum elevation (m) of high tides at Tofino cemetery and Meares Island

	Tide gauge, Tofino harbour	Cemetery	Meares Island
June 24, 1993	3.21	–0.64	—
July 14, 1994	3.18	—	–0.725
Maximum, summer 1994	3.7	–0.15	–0.205
Exceptional tide	4.1	0.25	0.195

Datum for tide gauge elevations is chart datum.

Datum for cemetery and Meares Island elevations is edge of forest.

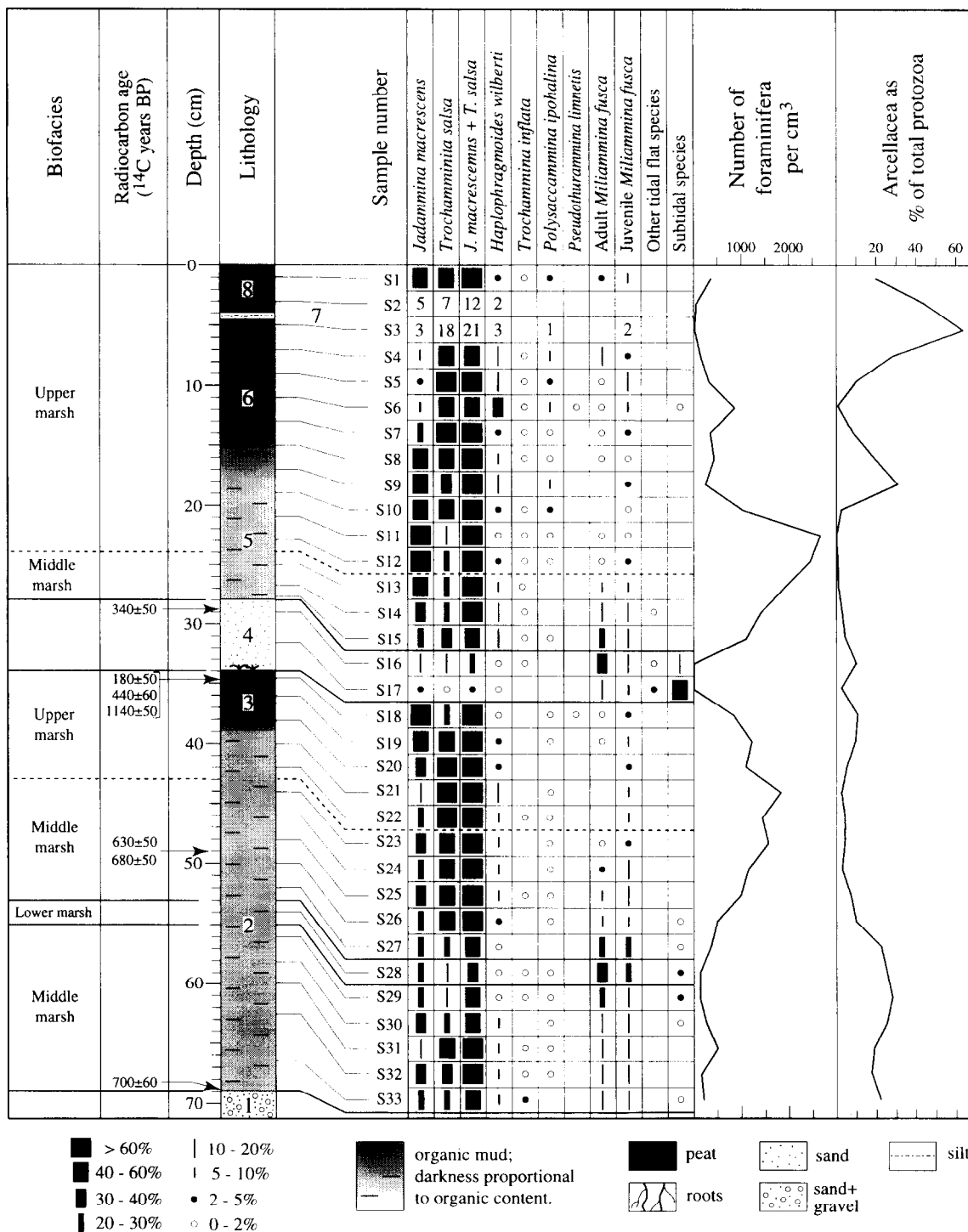


FIG. 4. Lithostratigraphy, radiocarbon ages and distribution of major foraminiferal taxa in the Meares Island section. There were small numbers of specimens in samples S2 and S3, therefore numbers of counted specimens are shown rather than percentages.

from 0 to 23 cm. At Meares Island, 37 modern samples were collected over a vertical range of 2.075 m. Over much of the transect, the samples are separated vertically by 4 to 6 cm; however, gaps of up to 12 cm exist. At both sites, an elevation of 0 m was arbitrarily assigned to the forest edge (=local datum).

The wall of the tidal channel at the cemetery site was cut back about 30 cm prior to sampling to preclude the possibility of contamination and destruction by oxidation

of foraminiferal tests. As mentioned previously, the Meares Island samples were collected from a freshly dug pit. At both sites, most samples were 2 cm thick and there were no gaps between them. The sampling interval above and below the top of the buried peat was reduced to 0.5–1 cm to capture, as much as possible, conditions immediately before and after the earthquake.

Sample processing methods are detailed in Guilbault *et al.* (1995). The Meares Island samples were stored in

TABLE 3. Total counts of foraminifera and arcellacea (stained + unstained) from the modern marsh at the Meares Island site
 Foraminifera/cm³: identified + indeterminate foraminifera; this is the value shown on Fig. 3.
 Biofacies: FW=freshwater; UM=upper marsh; MM=middle marsh; LM=lower marsh; TF=tidal flats

Sample number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Elevation (cm)	10	-9.5	-11.5	-23	-19.5	-25.5	-25.5	-30.5	-32.5	-34.5	-35.5	-40.5	-44.5	-48.5	-53.5	-57.5	-61.5	-65.5	
Foraminifera/cm ³	1	2	186	62	369	40	158	1057	32	1918	106	1699	414	2922	1762	2351	2580	2164	
Biofacies	FW	FW	UM	UM	UM	UM	UM	UM	UM	UM	UM	UM	UM	UM	MM	MM	MM	MM	
<i>Jadammina macrescens</i>	—	—	79	39	109	30	35	15	38	23	119	164	29	104	128	155	59	89	145
<i>Jadammina polystoma</i>	—	—	1	—	2	—	—	1	—	1	—	16	—	24	17	16	5	9	13
<i>Trochammina salsa</i>	—	1	79	3	98	5	55	72	1	111	5	309	48	90	176	143	91	93	145
<i>Trochammina irregularis</i>	—	—	4	1	18	2	26	23	—	20	2	36	35	20	15	9	17	24	29
<i>Haplophragmoides wilberti</i>	—	—	3	32	7	6	9	78	1	29	5	77	52	113	71	97	50	70	143
<i>H. wilberti</i> 8+ chambers	—	—	1	—	—	1	—	31	—	12	2	21	14	10	12	16	8	16	24
<i>Haplophragmoides manilaensis</i>	—	—	—	—	—	—	—	1	—	—	—	—	1	—	—	—	—	2	—
<i>Trochammina inflata</i>	—	—	2	—	1	1	—	31	—	24	—	89	—	112	60	28	15	32	53
<i>Siphotrochammina lobata</i>	—	—	—	—	—	—	1	6	—	1	—	2	—	1	—	—	—	1	—
<i>Trochammina ochracea</i>	—	—	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1
<i>Trochammina cf. nana</i>	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Polysaccamina ipohalina</i>	—	1	3	2	7	2	10	12	—	11	—	12	43	15	6	5	8	6	5
<i>Pseudothurammmina limnetis</i>	—	—	—	—	—	—	6	6	—	—	—	2	3	—	1	—	—	—	—
Adult <i>Miliammina fusca</i>	—	—	4	5	7	2	1	3	—	8	—	22	2	22	19	24	17	36	53
Young <i>Miliammina fusca</i>	—	—	15	4	16	—	16	40	—	92	—	284	8	187	80	74	40	79	65
<i>Ammotium salsum</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Ammobaculites exiguus</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Polysaccamina hyperhalina</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Indeterminate miliolid	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—
<i>Epistominella vitrea</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Glabratella luxuribulla</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Glabratella</i> sp.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Elphidium cf. lene</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Elphidium cf. frigidum</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Elphidium cf. williamsoni</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total identified foraminifera	0	2	194	86	265	49	159	319	40	332	133	1034	234	699	585	570	310	457	676
Indeterminate foraminifera	1	1	38	7	64	3	43	69	1	65	6	293	38	100	95	77	39	57	68
<i>Centropyxis aculeata</i>	—	17	9	41	23	25	70	29	81	6	67	11	42	1	2	1	—	—	15
<i>Centropyxis constrictus</i>	4	3	1	94	54	6	3	3	15	11	8	139	13	16	1	1	—	—	2
<i>Plagiopyxis</i> sp.	84	2	—	3	1	7	5	1	17	—	9	2	8	2	1	—	—	—	—
<i>Cyclopyxis cf. kahli</i>	—	2	—	3	2	3	3	1	14	1	13	—	1	—	—	—	—	—	—
<i>Cyclopyxis cf. puteus</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Trigonopyxis</i> sp.	—	—	—	—	—	—	1	1	1	—	3	—	2	—	—	—	—	—	—

TABLE 3. Continued

<i>Nebela cf. collaris</i>	—	3	—	2	—	1	2	3	—	—	4	—	—	—	2	—	—	—
<i>Nebela cf. tubulosa</i>	—	1	1	—	1	—	—	1	—	—	1	—	—	—	1	—	—	—
<i>Heleopera sphagni</i>	1	1	—	—	1	—	—	6	—	—	—	—	—	—	—	—	—	1
<i>Distomatopyxis couillardii</i>	—	1	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Diffugia globulus</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Diffugia oblonga</i>	—	1	—	2	—	10	7	21	1	6	2	5	—	—	—	—	—	—
<i>Diffugia protaeiformis</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Diffugia urceolata</i>	—	—	—	—	—	—	1	—	—	2	—	—	—	—	—	—	—	—
<i>Pontigulasia compressa</i>	—	—	—	1	—	1	2	—	4	—	2	—	—	—	—	—	—	—
<i>Phryganella</i> sp.	—	—	—	2	—	5	2	—	5	2	—	4	—	—	—	—	—	1
<i>Assulina</i> sp.	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—
Total identified acellacea	89	31	11	148	80	61	96	169	21	111	154	87	19	4	5	0	0	19
Indeterminate acellacea	2	0	0	0	0	0	3	1	3	0	0	2	0	0	0	0	0	0
Sample number	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Elevation (cm)	—70.5	—82.5	—85.5	—88.5	—92.5	—96.5	—99.5	—102.5	—106.5	—112.5	—117.5	—120.5	—126.5	—130.5	—135.5	—136.5	—157.5	—197.5
Foramifera/cm ³	2066	752	490	236	241	868	637	1415	1489	535	364	83	101	186	200	578	488	141
Biofacies	MM	MM	MM	LM	LM	LM	LM	LM	LM	LM	LM	LM	TF	TF	TF	LM	TF	TF
<i>Jadammina macrescens</i>	248	111	77	52	39	22	42	44	254	24	23	3	2	3	2	38	32	30
<i>Jadammina polysstoma</i>	27	18	10	10	13	4	6	11	54	2	7	1	—	2	1	9	5	8
<i>Trochammina salsa</i>	198	38	33	24	15	10	88	5	36	2	—	1	—	1	—	1	—	2
<i>Trochammina irregularis</i>	40	19	12	6	2	5	24	4	10	—	3	1	—	—	—	—	1	5
<i>Haplophragmoides wilberti</i>	162	23	15	6	5	24	142	48	137	21	25	1	—	2	—	26	17	29
<i>H. wilberti</i> 8+ chambers	9	3	—	—	—	1	11	1	8	4	1	—	—	—	—	3	—	—
<i>Haplophragmoides manilaensis</i>	3	—	—	—	—	—	—	2	—	—	1	—	—	—	—	—	—	—
<i>Trochammina inflata</i>	88	13	32	4	3	4	—	39	155	3	3	1	—	—	33	2	3	3
<i>Siphotrochammina lobata</i>	3	—	4	—	—	—	—	—	1	—	—	—	—	—	—	—	—	1
<i>Trochammina ochracea</i>	—	—	—	—	—	—	—	—	—	1	—	1	—	—	—	—	1	15
<i>Trochammina cf. nana</i>	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—
<i>Polysaccamina ipohalina</i>	27	36	16	2	25	7	7	3	12	—	—	—	—	—	—	2	—	—
<i>Pseudothurammmina linnetis</i>	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—
Adult <i>Miliammina fusca</i>	152	84	67	111	128	181	109	179	285	239	155	153	102	166	152	141	362	483
Young <i>Miliammina fusca</i>	78	40	24	79	66	43	51	55	102	87	61	57	21	18	23	51	94	126
<i>Ammotium salsum</i>	—	—	—	1	—	—	—	—	—	2	—	2	6	4	5	—	—	2
<i>Ammobaculites exiguus</i>	—	—	—	1	1	—	1	—	2	2	2	15	6	4	7	1	2	3
<i>Polysaccamina hyperhalina</i>	—	—	—	1	—	—	1	1	2	3	3	6	21	29	25	8	11	4
Indeterminate miliolid	—	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—	—	—
<i>Epistominella vitrea</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Glabratella luxuribulla</i>	—	—	—	—	—	—	1	2	—	2	1	1	—	—	—	—	—	—

methanol instead of formaldehyde, as was done with the cemetery samples, because of the toxicity of formaldehyde. Methanol was added to the modern samples in the field and to the fossil samples one week later in the laboratory. After sieving, modern samples from both sites were fixed in formaldehyde and stained with Rose Bengal. Fixing and staining took at least two days for the cemetery samples and one week or more for the Meares Island samples. Excess stain was then washed away and the residues were placed in methanol for long-term storage. The stained specimens were counted separately, but the quantitative analysis of the modern data set that follows is based on sums of living and dead specimens. Counted fractions are stored at the senior author's laboratory in Montreal.

RESULTS

Modern Transects

Counts of foraminifera and arcellacea for samples collected along the modern transect at the cemetery site are reported in Guilbault *et al.* (1995); data for the Meares Island transect are presented in Table 3. Generalized percentage data for key taxa are displayed in Figs 5 and 6.

There are three biofacies at both localities: (1) the unvegetated tidal flat and the lower marsh biofacies dominated by *Miliammina fusca*; (2) the upper marsh biofacies dominated by *Jadammina macrescens* and *Trochamminita salsa*; and (3) the supratidal biofacies dominated by arcellacea. The upper and lower marsh are defined on the basis of their foraminiferal biofacies and not vegetation.

The tidal flat at Meares Island can be distinguished from the low marsh by a greater number of tidal flat species other than *M. fusca* (*Ammobaculites exiguus*, *Ammotium salsum* and *Polysaccammina hyperhalina*) and by a very low *J. macrescens* and *T. salsa* content. However, total numbers of 'other tidal flat foraminifera' are rather small (maximum=22% of total; generally much less), and the definition of a separate biofacies does not seem justified, at least for the purpose of this paper. The single tidal flat sample at the cemetery section is faunally indistinguishable from the lower marsh.

The limit between the upper and lower marsh is set at the level where the sum of *J. macrescens* and *T. salsa* becomes greater than the sum of adult and juvenile *M. fusca*. Guilbault *et al.* (1995) counted many of the *T. salsa* in samples from the cemetery site as *J. macrescens* morphotype *polystoma* (see Remarks on Morphotypes in

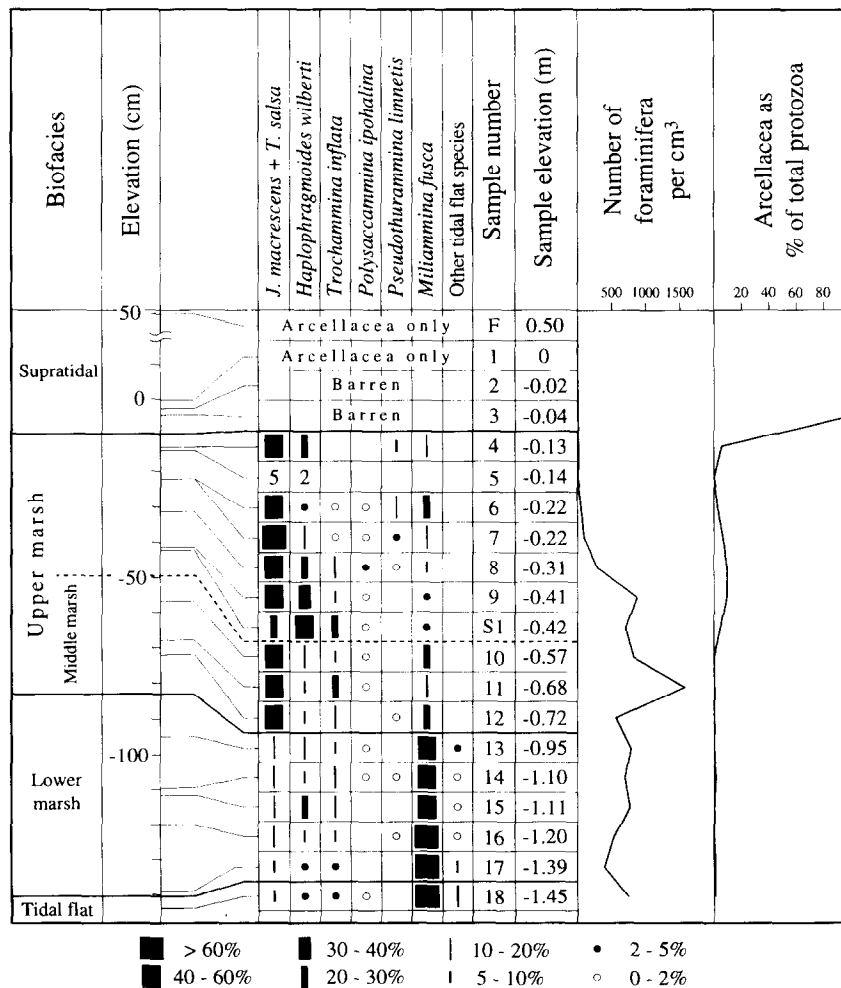


FIG. 5. Distribution of total foraminiferal microfauna (stained and unstained) along the modern transect at the cemetery site. *Miliammina fusca* percentages have been corrected using the '*M. fusca* factor' of Guilbault *et al.* (1995).

Appendix). Grouping *J. macrescens* and *T. salsa* allows data from the two study sites to be compared, while not changing the position of the high marsh-low marsh boundary at the cemetery site. There are two peaks of *J. macrescens* in the upper marsh at Meares Island, one from -11.5 to -35.5 cm elevation and the other from -48.5 to -85.5 cm (Fig. 6). *Trochammina salsa* is generally high

from -25.5 to -70.5 cm and is especially abundant at -11.5 and -19.5 cm. These trends vanish when the two species are combined; their sum gradually increases towards the top of the transect.

The *M. fusca* population at Meares Island is predominantly juvenile in the upper part of the upper marsh (Fig. 6; Remarks on Morphotypes in Appendix), as at the

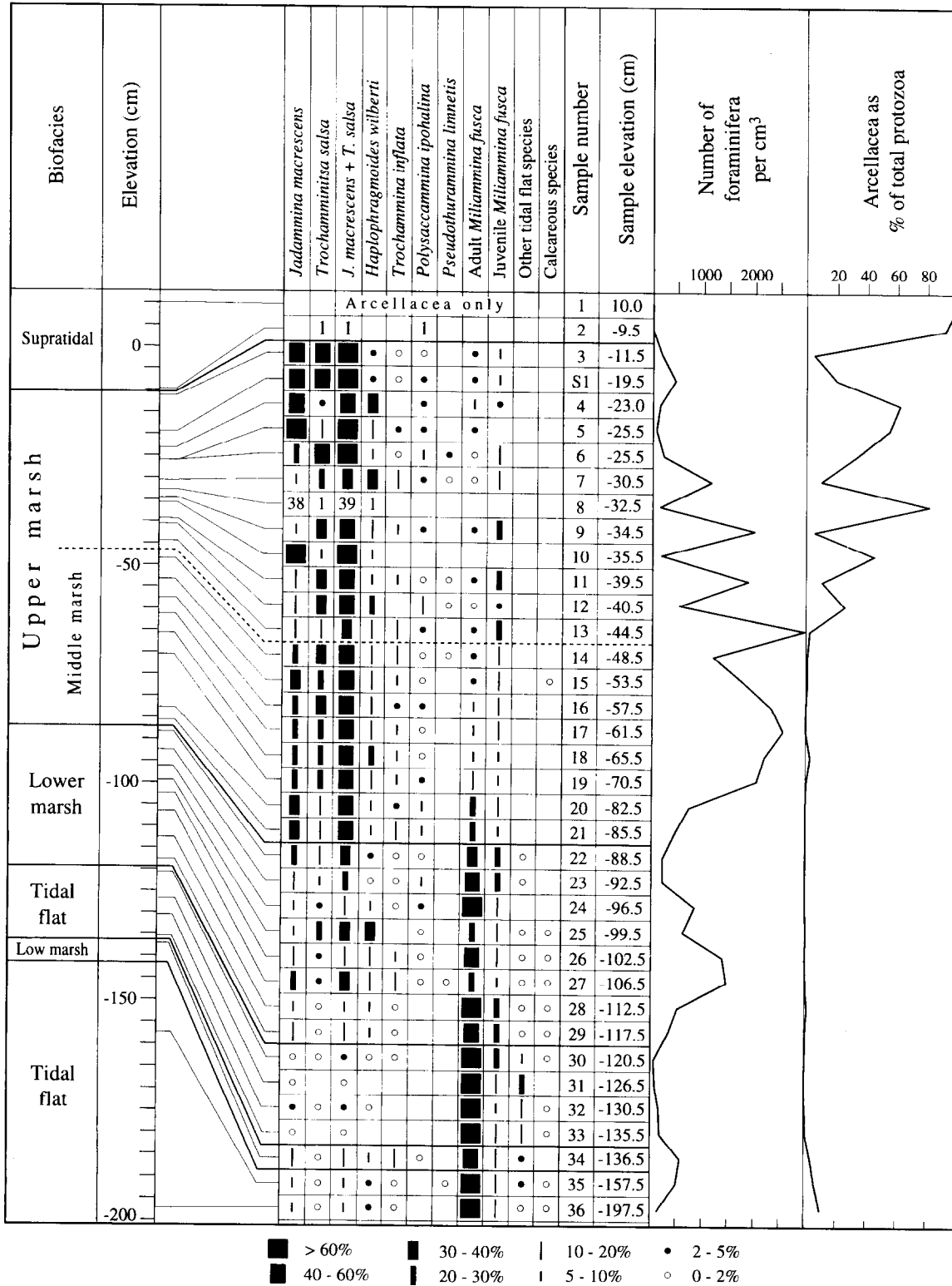


FIG. 6. Distribution of total foraminiferal microfauna (stained and unstained) along the modern transect at the Meares Island site.

cemetery site (Guilbault *et al.*, 1995). The interval between the top of the lower marsh and the point where the juvenile:adult ratio first reaches 8:1 or more constitutes a subfacies of the upper marsh called the 'middle marsh', which is recognized at both sites.

Haplophragmoides wilberti and *T. inflata* show little correlation with elevation. *H. wilberti* may be more closely controlled by salinity than elevation (Scott *et al.*, 1990). The closely related species *Haplophragmoides manilaensis* prefers brackish settings (Scott and Medioli, 1980; Scott *et al.*, 1991; de Rijk, 1995). Meares Creek, however, does not seem to have any effect on its numbers in the upper part of the Meares Island transect.

Almost all observed calcareous specimens were living (stained), and even those showed signs of dissolution. Most belong to the genera *Elphidium* and *Glubratella*. The total of calcareous specimens never exceeds 1.22% of any assemblage. Ostracodes are present in many samples, although in small numbers; most, like the calcareous foraminifera, were living and many were decalcified.

Samples above -22 cm at the cemetery site either have a limited fauna or are barren. This may be due to the relative dryness of the substrate. As a result, interpretation of paleoelevations above -22 cm at that site is difficult and reliability is poor (Guilbault *et al.*, 1995).

Samples 34, 35 and 36 from the Meares Island tidal flat contain up to 10% arcellacea (Table 3), presumably introduced by Meares Creek. Similarly, *J. macrescens* and *H. wilberti* in these samples may have been carried in by Meares Creek. The highest part of the Meares Island transect, near the forest edge (north of 140 m on Fig. 2(b)), is in a topographically irregular and somewhat depressed area that is strongly influenced by Meares Creek. This leads to assemblages that differ slightly from those observed below, with more than 60% *J. macrescens* + *T. salsa* and variable percentages of arcellacea (locally greater than the percentage of foraminifera).

The top of the Meares Island marsh is considered to lie between -9.5 and -11.5 cm elevation (Fig. 6). The unsampled interval between 0 and -9.5 cm may contain some foraminifera, but the presence of alders at -9.5 cm (Fig. 2(b)) indicates supratidal conditions at that elevation. The highest sample, at $+10$ cm, has a completely different arcellacea composition (*Plagiopyxis* sp.), which probably reflects the fact that this is not a marsh but a forest floor.

Correlation Between the Cemetery and Meares Transects

Figure 7 compares elevations of marsh zones along the cemetery and Meares Island transects. Despite a general similarity, there are uncertainties that limit an exact comparison of the two sites. The top of the marsh is 10 cm below the forest edge at both sites, but at the cemetery this value is approximate because it is interpolated between a foraminifer-bearing sample at -17 cm and a barren sample at -4 cm. The upper marsh-

lower marsh boundary at Meares Island is precisely defined at -87 ± 1.5 cm, whereas at the cemetery it occurs in an unsampled interval between -72 and -95 cm. The lowermost patch of the vegetation at Meares Island, at -136.5 cm, is within 1 cm of the elevation of the base of the marsh at the cemetery site. However, that patch of vegetation is, at best, a poor indicator of the level of the base of the marsh. The middle-upper marsh boundary at Meares Island is known to within a few centimeters (between -44.5 cm and -48.5 cm), whereas at the cemetery site it is poorly constrained within the broad interval between -42 cm and -57 cm.

Figure 7 also shows the highest level reached by tides on the respective days on which the two sites were sampled. By chance, on both days, the tide reached about the same level at the tidal gauge at Tofino (3.21 m and 3.18 m).

In summary, the marsh zones appear to be consistent in elevation along Browning Passage, but the uncertainties are such that we prefer to interpret each fossil section only on the basis of its associated modern transect.

Sections

Results of foraminiferal analysis of samples from the cemetery section can be found in Guilbault *et al.* (1995); the tallies for the Meares Island section are given in Table 4. Generalized results for the two sites are displayed in Figs 3 and 4. All foraminiferal species that occur along the transects are also found in the sections, with the exception of calcareous foraminifera which probably have undergone post-mortem dissolution. *Pseudothurammia limnetis* is rare in the sections, but also is known to be sensitive to post-mortem destruction (Scott *et al.*, 1981).

At the cemetery section (Fig. 3), the pre-earthquake succession begins with a tidal flat and lower marsh assemblage dominated by *M. fusca*. There is a gradual change upward into a clearly defined middle marsh interval dominated by *J. macrescens* and *T. salsa*, with abundant adult *M. fusca*, followed by upper marsh assemblages with high *J. macrescens*-*T. salsa* and juvenile : adult *M. fusca* ratios of 8:1 or more. The post-earthquake deposits show a similar regressive trend. At Meares Island (Fig. 4), the pre-earthquake succession begins abruptly in the middle marsh and, after a brief incursion in the lower marsh, returns to the middle marsh and finally reaches the upper marsh. Above the tsunami sand, there is a brief middle marsh interval which is succeeded by upper marsh assemblages that extend to the top of the section.

Differences between the two sections arise in part from their difference in elevation. The top of the cemetery section is 42 cm below the forest edge, whereas the top of the Meares Island section is 19.5 cm below this datum. This may explain why only one of the Meares Island samples records a lower marsh environment. Even the first marsh sample above the coseismically subsided marsh surface on Meares Island contains too few *M. fusca* to be called lower marsh. In contrast, the sample from the

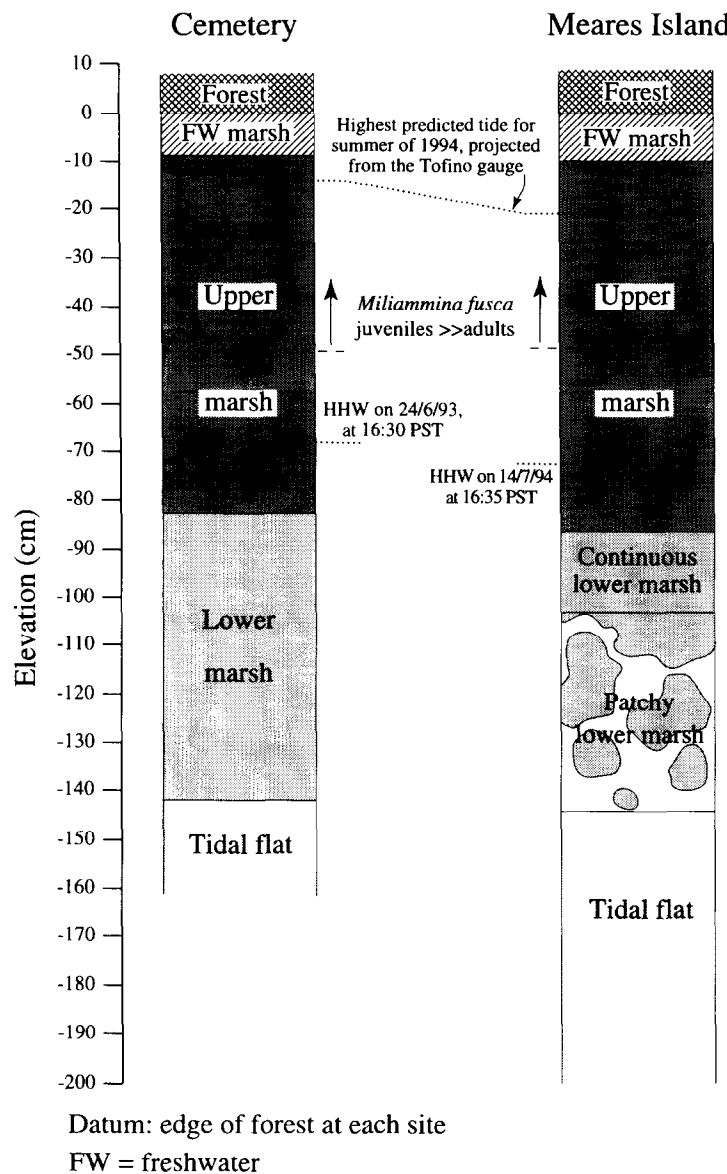


FIG. 7. Vertical distribution of modern biofacies at the cemetery and Meares Island sites. The horizontal dashed lines mark the upper limit of the 'middle marsh', above which the juvenile : adult ratio of *M. fusca* is greater than 8:1.

same stratigraphic level at the cemetery site is fully representative of a lower marsh environment.

Arcellacea are much better represented at the Meares Island site, both in terms of numbers and diversity, and their occurrence does not seem related to the foraminiferal biofacies. In contrast, in the cemetery section, arcellacea are more common in the upper marsh assemblages. This may reflect the influence of Meares Creek, since modern data show clearly that areas close to the creek contain abundant arcellacea, even as far down as the tidal flat. In general, arcellacea indicate the amount of freshwater input rather than elevation (Scott *et al.*, 1980).

Microfauna of Tsunami Sediments

The tsunami sand at Meares Island contains marsh foraminifera as well as species found in subtidal settings (Table 5). The presence of species that live only at

elevations lower than the tidal marsh is strong evidence that the sand was transported landward and is not, for example, a fluvial deposit. *Trochammina nana* and *eggerella advena* are common subtidal species that are extremely rare in tidal marshes, and we are unaware of any report of *Cribrostomoides jeffreysii* from marshes. *Trochammina ochracea* is common and may be locally dominant in Quaternary sediments off the British Columbia coast (J.-P. Guilbault and R.T. Patterson, unpublished data), but it is less indicative since it can be found in small numbers throughout tidal marshes (Table 3). All of these 'subtidal' specimens could as well have been transported from the lower part of the tidal flats, which we have not sampled, but they nevertheless constitute irrefutable evidence of landward transport.

The thin silt layer at 4–4.5 cm depth in the Meares Island section may have been deposited by the 1964 Alaska tsunami. This is the largest of the historical tsunamis on the British Columbia coast, reaching 2.47 m elevation at Tofino (Thomson, 1981, Table 9.1). The

TABLE 4. Continued.

	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32	S33
<i>Difflugia bacilliarium</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Difflugia lithophila</i>	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Difflugia oblonga</i>	—	2	5	1	1	5	4	2	—	—	—	—	—	—	—	—
<i>Difflugia urceolata</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Lagenodifflugia vas</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Pontigulasia compressa</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Phryganella</i> sp.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Assulina</i> sp.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total identified arcellacea	80	16	62	25	14	3	23	62	77	11	0	2	4	19	14	10
Indeterminate arcellacea	0	1	3	0	0	0	0	1	0	0	0	0	0	0	0	0
Sample number	S18	S19	S20	S21	S22	S23	S24	S25	S26	S27	S28	S29	S30	S31	S32	S33
Depth (cm)	34—	35—	37—	39—	41—	43—	45—	47—	49—	51—	53—	55—	57—	59—	61—	64—
Foraminifera/cm ³	35	37	39	41	43	45	47	49	51	53	55	57	59	61	64	69
	835	1218	1092	1826	1436	1567	1149	991	498	364	141	132	270	507	160	210
Biofacies	UM	UM	UM	UM	UM	MM	MM	MM	MM	MM	LM	MM	MM	MM	MM	MM
<i>Jadammina macrescens</i>	199	204	121	51	54	96	57	112	54	76	40	60	66	28	94	77
<i>Jadammina polystoma</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Trochammina salsa</i>	74	143	199	138	130	150	107	132	122	48	22	32	48	65	77	52
<i>Trochammina irregularis</i>	12	30	35	35	30	17	4	7	2	5	3	2	3	8	14	14
<i>Haplophragmoides wilberti</i>	3	16	11	27	24	16	13	20	11	3	2	4	15	12	16	23
<i>H. wilberti</i> 8+ chambers	—	—	—	2	1	—	—	3	—	1	—	—	—	—	—	—
<i>Haplophragmoides manilaensis</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Trochammina inflata</i>	—	—	—	—	2	—	—	—	—	—	3	1	—	—	—	—
<i>Siphotrochammina lobata</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Trochammina ochracea</i>	—	—	—	—	—	—	—	1	—	2	4	9	1	—	—	5
<i>Remaneica helgolandica</i>	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—
<i>Trochammina nana</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Cribrostomoides jeffreysii</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Eggerella advena</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Polysaccamina ipohalina</i>	2	1	—	4	1	3	2	1	1	—	1	1	1	1	4	—
<i>Pseudothurammmina limnetis</i>	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Adult <i>Miliammina fusca</i>	1	5	—	—	—	2	10	20	21	69	71	57	41	21	45	44
Juvenile <i>Miliammina fusca</i>	11	26	19	25	23	13	22	41	21	55	45	40	35	26	39	49
<i>Ammobaculites exiguus</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total identified foraminifera	303	425	386	282	265	297	215	337	233	259	192	209	211	162	292	270
Indeterminate foraminifera	44	24	44	29	38	31	22	47	39	16	14	22	25	33	35	37
<i>Arcella</i> sp.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Centropyxis aculeata</i>	34	38	21	1	7	4	3	14	15	29	28	29	23	8	19	38
<i>Centropyxis constrictus</i>	6	4	2	3	5	4	2	3	2	12	11	8	19	9	11	15

TABLE 4. Continued.

<i>Plagiopyxis</i> sp.	—	1	—	2	—	1	4	1	2	4	10	12	16	5	6	12	3
<i>Cyclopyxis</i> cf. <i>kahli</i>	—	1	—	—	—	—	—	—	—	—	—	1	1	—	—	1	1
<i>Cyclopyxis</i> cf. <i>puteus</i>	—	—	—	—	1	—	—	—	1	—	1	—	1	—	—	—	—
<i>Trigonopyxis</i> sp.	—	—	—	—	3	—	1	—	—	—	—	1	2	3	2	5	1
<i>Hyalosphenia</i> sp.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	1
<i>Nebela</i> cf. <i>collaris</i>	—	1	—	—	—	—	—	—	—	—	1	—	1	1	—	—	2
<i>Nebela</i> cf. <i>tubulosa</i>	—	—	—	—	—	—	—	—	—	—	2	1	2	2	1	5	—
<i>Heleopera</i> <i>sphagni</i>	—	—	—	—	—	—	—	—	—	—	2	1	2	2	1	1	—
<i>Distomatopyxis</i> <i>couillardii</i>	—	—	—	—	—	—	—	—	—	—	—	1	2	2	1	1	1
<i>Difflugia</i> <i>bacillaritarum</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1
<i>Difflugia</i> <i>lithophila</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Difflugia</i> <i>oblonga</i>	—	—	—	—	—	—	—	—	4	5	16	6	20	19	8	5	17
<i>Difflugia</i> <i>urceolata</i>	—	—	—	—	—	—	—	—	—	—	4	—	3	2	3	2	3
<i>Lagenodifflugia</i> <i>vas</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
<i>Pontigulastia</i> <i>compressa</i>	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	2	1
<i>Phryganella</i> sp.	—	—	—	—	—	—	1	—	1	3	2	4	3	1	3	—	—
<i>Assulina</i> sp.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Total identified arcellacea	40	45	23	6	28	13	14	6	28	29	77	65	88	77	43	64	84
Indeterminate arcellacea	0	0	0	1	1	0	0	0	1	0	1	3	0	1	2	5	2

TABLE 5. Microfaunal content of the lower part of the tsunami sand at the Meares Island section (sample S17, Fig. 4)

Species	Number	%
<i>Trochammina nana</i>	62	38
<i>Miliammina fusca</i> (adult + juvenile)	39	24
<i>Eggerella advena</i>	22	14
<i>Trochammina ochracea</i>	14	9
<i>Cribrostomoides jeffreysii</i>	6	4
<i>Ammobaculites exiguus</i>	6	4
<i>Jadammina macrescens</i>	3	2
<i>Remaneica helgolandica</i>	2	1
<i>Trochammina salsa</i>	2	1
<i>Plagiopyxis</i> sp.	2	1
<i>Diffugia oblonga</i>	2	1
<i>Jadammina polystoma</i>	1	1
<i>Haplophragmoides wilberti</i>	1	1
Indeterminates	10	—
Total	172	

%; Rounded values.

sample from 4–6 cm depth, which includes the silt layer, does not have an unusual faunal content that would support a tsunami origin, but the sample below it contains an anomalously high percentage of adult *M. fusca*.

Statistical analysis assigns to this last sample a paleoelevation at least 25 cm lower than that of samples directly above and below it. Since there is no other evidence for a sudden change in relative sea level of this magnitude in recent time, we interpret these *M. fusca* as reworked from the lower marsh by the 1964 tsunami. They do occur 2 cm lower than expected, but it is possible that they were carried alive from the lower marsh and subsequently buried themselves in the sediment to escape the either too dry or too hyposaline conditions at the surface of the upper marsh. Bioturbation by other organisms is an unsatisfactory explanation because some adult *M. fusca* would be present in the 4–6 cm sample.

STATISTICAL ANALYSIS AND INTERPRETATION

We first estimated paleoelevations by visually comparing the distributions of the modern and fossil data in the same way as was done by Guilbault *et al.* (1995). The interpretation that follows is based mainly on statistical analysis, but the two approaches yielded similar results.

We began by performing Q-mode factor analysis

TABLE 6. B-Hat matrix and paleoelevations for samples from the cemetery section (modified from Guilbault *et al.*, 1995)

Sample no.	Sample depth (cm)	Communality	Factor 1 (<i>J. macrescens</i> + <i>T. salsa</i>)	Factor 2 (<i>M. fusca</i>)	Calculated paleoelevation (cm)
S1	0–2	0.9919	0.5376	0.1126	–49
S2	2–4	0.9977	0.7337	0.1169	–38
S3	4–6	0.9995	0.7902	0.0688	–32
S4	6–8	0.9985	0.7847	0.1953	–40
S5	8–10	0.8995	0.8796	0.0842	–28
S6	10–12	0.9864	0.9884	0.0941	–22
S7	12–14	0.9819	0.9908	0.0026	–16
S8	14–16	0.9783	0.9881	0.0431	–19
S9	16–18	0.9809	0.9902	0.0141	–17
S10	18–20	0.9860	0.9853	0.1058	–23
S11	20–22	0.9925	0.9874	0.1221	–24
S12	22–24	0.9967	0.8692	0.4451	–52
S13	24–26	0.9854	0.7601	0.3853	–54
S14	26–27	0.9988	0.5594	0.7037	–87
S15	27–28	0.9898	0.9927	0.0087	–16
S16	28–30.5	0.9896	0.9932	0.0244	–17
S17	30.5–33	0.9607	0.9755	0.0933	–23
S18	33–35	0.9899	0.9882	0.1002	–23
S19	35–37	0.9912	0.9899	0.1052	–23
S20	37–39	0.9935	0.9811	0.1599	–27
S21	39–41	0.9942	0.9152	0.3585	–44
S22	41–43	0.9855	0.9343	0.2624	–36
S23	43–45	0.9966	0.7103	0.6176	–73
S24	45–47	0.9941	0.7707	0.5624	–66
S25	47–49	0.9919	0.3203	0.9169	–114
S26	49–51	0.9895	0.2323	0.9624	–122
S27	51–55	0.9839	0.1257	0.9814	–130
S28	55–60	0.9888	0.0656	0.9899	–134

Regression equation: Paleoelevation = -66.337 (factor 1) + 56.495 (factor 2) -71.728 .
Standard error of estimate, adjusted for degree of freedom: ± 15.8 cm.

TABLE 7. B-Hat matrix and paleoelevations for samples from the Meares Island section

Sample no.	Sample depth (cm)	Communality	Factor 1 (<i>J. macrescens</i> + <i>T. salsa</i>)	Factor 2 (<i>M. fusca</i>)	Factor 3 (<i>H. wilberti</i>)	Calculated paleoelevation (cm)
S1	0-2	0.9986	0.9927	0.1146	-0.0023	-29
S2	2-4	0.9794	0.9827	0.0660	0.0966	-24
S3	4-6	0.9965	0.9911	0.0939	0.0731	-28
S4	6-8	0.9704	0.9083	0.3575	0.1329	-61
S5	8-10	0.9913	0.9712	0.1412	0.1677	-36
S6	10-12	0.9571	0.8455	0.1112	0.4795	-33
S7	12-14	0.9981	0.9949	0.0906	0.0064	-26
S8	14-16	0.9900	0.9911	0.0738	0.0482	-25
S9	16-18	0.9932	0.9895	0.0824	0.0853	-27
S10	18-20	0.9966	0.9958	0.0702	-0.0095	-23
S11	20-22	0.9946	0.9944	0.0684	-0.0329	-22
S12	22-24	0.9952	0.9947	0.0735	-0.0197	-23
S13	24-26	0.9952	0.9782	0.1939	0.0254	-40
S14	26-27.5	0.9918	0.9436	0.2960	0.1178	-54
S15	27.5-28	0.9901	0.8776	0.4506	0.1298	-73
S18	34-35	0.9969	0.9950	0.0782	-0.0285	-24
S19	35-37	0.9963	0.9934	0.0974	0.0078	-27
S20	37-39	0.9962	0.9949	0.0798	-0.0051	-24
S21	39-41	0.9956	0.9889	0.0991	0.0886	-29
S22	41-43	0.9955	0.9892	0.0982	0.0858	-29
S23	43-45	0.9960	0.9943	0.0861	0.0083	-26
S24	45-47	0.9959	0.9837	0.1598	0.0518	-36
S25	47-49	0.9940	0.9772	0.1872	0.0624	-40
S26	49-51	0.9959	0.9754	0.2094	0.0261	-42
S27	51-53	0.9770	0.8003	0.5794	0.0284	-84
S28	53-55	0.9752	0.5731	0.8034	0.0374	-104
S29	55-57	0.9798	0.7789	0.6099	0.0334	-87
S30	57-59	0.9898	0.8866	0.4403	0.0994	-71
S31	59-61	0.9903	0.9351	0.3238	0.1054	-57
S32	61-64	0.9961	0.9358	0.3416	0.0604	-59
S33	64-69	0.9854	0.8870	0.4188	0.1528	-69

Regression equation: Paleoelevation = -45.319 (factor 1) -135.467 (factor 2) -23.461 (factor 3) + 31.333.
Standard error of estimate, adjusted for degrees of freedom: ± 13.0 cm.

(CABFAC program of Imbrie and Kipp, 1971) on the modern data. Two matrices were obtained: the varimax factor component matrix (factors vs. sites) and the varimax factor score matrix (factors vs. species). Then, we executed stepwise multiple regression analysis on the varimax factor component matrix and obtained a regression equation (the 'transfer function') which gives elevation as a function of species composition (REGRESS program of Imbrie and Kipp, 1971). Fossil foraminiferal assemblages were factored by applying the program THREAD (Imbrie and Kipp, 1971) to the varimax factor score matrix derived from the modern samples. This yielded a varimax factor component matrix (B-Hat matrix, Tables 6 and 7). The transfer function determined from REGRESS was then applied to the data in the B-Hat matrix to calculate paleoelevations of the fossil samples (Tables 6 and 7).

We initially used all of the taxonomic categories and all of the samples at each of the two sites. Then, we removed, one at a time, those taxa or samples that could bias the results. Supratidal samples weaken the linear correlation between *J. macrescens* and elevation because

that species peaks in the upper marsh and disappears in the supratidal area. In addition, freshwater samples provide no information about elevations in the marsh. The removal of the single freshwater sample from the cemetery transect allowed a good correlation between *J. macrescens* and elevation, leading to the estimate of coseismic relative sea level change of 57 cm reported by Guilbault *et al.* (1995).

At Meares Island, the analysis was more complex because there is a larger number of taxonomic categories. The separation of *T. salsa* and *J. macrescens* left both species as poor elevation indicators (Table 8), even though they are known to concentrate in the upper marsh. We solved this problem by grouping *J. macrescens* and *T. salsa*. Both species have variable distributions, but their combined numbers correlate well with elevation ($R=0.82$, Table 8). Then, we removed the two supratidal samples at the top of the transect for the same reason as at the cemetery site. Also, we removed tidal flat samples 31 to 36 because, below a certain elevation, there is no more faunal variation except that resulting from material transported by Meares Creek. Finally, we removed the

TABLE 8. Correlation between elevation and species percentage at Meares Island

Species	Correlation coefficient (R):		
	With freshwater samples and arcellacea	Freshwater samples removed with arcellacea	without arcellacea
<i>Jadammina macrescens</i> (+ <i>polystoma</i>)	+0.086	+0.333	+0.488
<i>Trochammina salsa</i> (+ <i>irregularis</i>)	+0.336	+0.544	+0.634
<i>J. macrescens</i> + <i>T. salsa</i>	+0.279	+0.595	+0.816
<i>Haplophragmoides wilberti</i>	-0.033	+0.004	+0.202
<i>Polysaccammina ipohalina</i>	+0.018	+0.070	+0.168
<i>Trochammina inflata</i> (+ <i>S. lobata</i>)	-0.167	-0.077	-0.041
Adult <i>Miliammina fusca</i>	-0.877	-0.896	-0.889
Juvenile <i>M. fusca</i>	-0.553	-0.473	-0.403
Total <i>M. fusca</i>	-0.874	-0.872	-0.858
Sum of arcellacea	+0.689	+0.596	—

All tidal flat samples except the highest one (no. 30, Fig. 6) have been removed from the data set.

arcellacea because their modern distribution shows they are mostly redeposited by Meares Creek.

CABFAC yielded 3 factors that explain 96.8% of the variance of the Meares Island data. Factor 1 is dominated by the sum of *J. macrescens* and *T. salsa* and accounts for 75.2% of the variance; it characterizes the upper marsh. Factor 2 (18.6% of the variance), dominated by adult *M. fusca*, is characteristic of the lower marsh. Factor 3 (3.0%) is dominated by *H. wilberti*; its significance is not known.

To harmonize the results from the two sites, we reran the cemetery data with *J. macrescens* and *T. salsa* grouped, and arcellacea removed. We also removed one modern cemetery sample that contained only seven specimens (sample 5) and was thus statistically invalid. The numbers of *M. fusca* were modified by the '*M. fusca* factor' as in Guilbault *et al.* (1995). CABFAC produced three factors that explain 98.5% of the variance. They are the same factors as at Meares Island and account for 70.7%, 23.1% and 4.7% of the variance, respectively. REGRESS considered only the first two factors (*J. macrescens*-*T. salsa* and adult *M. fusca*) in the regression equation, rejecting the third (*H. wilberti*).

Figure 8 shows paleoelevation curves for the two sections, along with standard errors calculated by the program REGRESS. The confidence intervals for statistically calculated modern elevations are compared to measured elevations in Fig. 9(a,b). The mean absolute value of residuals at the cemetery is about the same as reported by Guilbault *et al.* (1995) (11.2 cm vs. 11.9 cm), as are the correlation between calculated and measured elevations (Fig. 9(c); 0.949 vs. 0.941), and the correlation between measured elevations and residuals (Fig. 9(e); 0.315 vs. 0.337). At Meares Island, the mean absolute value of residuals is 10.7 cm, the correlation between calculated and measured elevations is 0.936, and the correlation between measured elevations and residuals is 0.352 (Fig. 9(d,f)). Correlation coefficients in the 0.3 to 0.4 range indicate that there is no systematic correlation between residuals and measured elevations (Fig. 9(e,f)).

Examination of Fig. 8 reveals that a sudden rise in relative sea level (i.e. submergence) terminated deposi-

tion of the buried peat. This submergence is a manifestation of subsidence during a large earthquake, probably the last great plate-boundary earthquake on the Cascadia subduction zone (Clague and Bobrowsky, 1994a). The magnitude of the submergence is similar at the two study sites. The mean value for the cemetery site is 71 cm (Table 9), whereas the mean value for the Meares Island site is 55 cm, which includes the difference in paleoelevation between the top and base of the tsunami sand (49 cm) plus the thickness of the sand itself (6 cm).

In the pre-earthquake part of the Meares Island section, there is an apparent submergence of about the same magnitude as the coseismic subsidence that is the focus of our work. The change from upper to lower marsh is too large to be explained by errors in paleoelevation estimates (Fig. 8), or by irregularities in the distribution of fauna in the lower marsh. The submergence is not likely due to compaction or mass movement, and probably is not the result of an earlier earthquake, as the change occurs over a few samples and thus is gradual. A seismic subsidence and rapid eustatic sea level rise are possible explanations.

DISCUSSION

The discussion of Guilbault *et al.* (1995) is worth reviewing in light of the new data from Meares Island. The limitations due to the small size of the previous paper's data base are much less of a problem now that a better sampled transect from another site that is more exposed to marine influence has given comparable results. We nevertheless maintain that it is preferable to interpret sections on the basis of close modern transects because of local site differences such as the presence or absence of streams. The vertical sampling interval that we used at Meares Island is sufficient to provide a good resolution of the vertical faunal changes. Problems are more likely to result from irregularities in distribution such as the low *M. fusca* contents of some lower marsh samples (nos 25 and 27, Fig. 6). However, the confidence interval for the calculated elevations (Fig. 9(b)) completely encloses the measured elevations along the

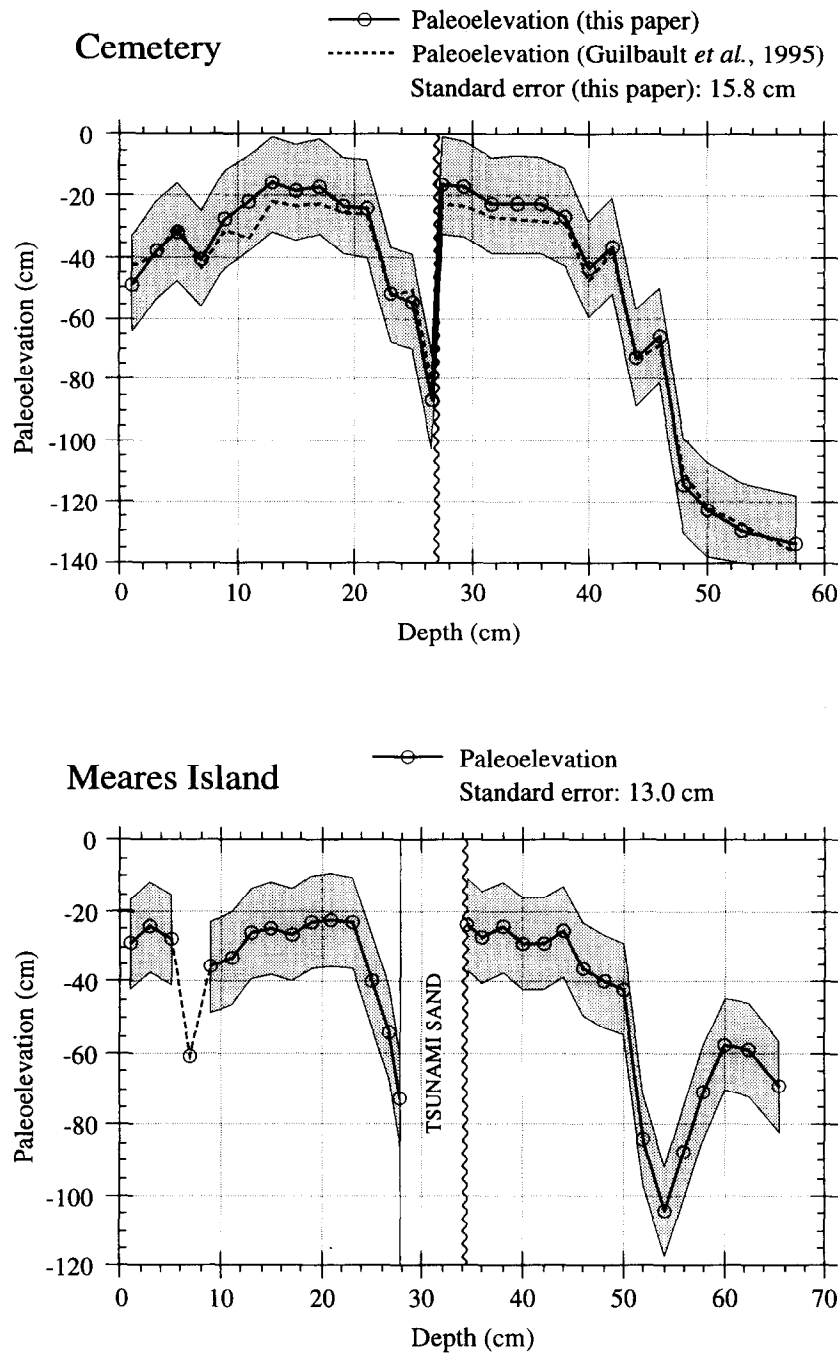


FIG. 8. Graphs of calculated paleoelevations for the cemetery and Meares Island sections determined by stepwise multiple regression analysis. The wavy vertical line marks the discontinuity at the top of the buried peat. The discontinuity coincides with a sharp decline in paleoelevation. The shaded envelope is the standard error of estimate calculated by the program REGRESS. The dashed segment in the Meares Island graph corresponds to sample S4, where faunal elements, probably reworked landward by the 1964 Alaska tsunami, skew the paleoelevation estimate.

transect. This means that all calculated elevations are reliable within the given margin of error.

Guilbault *et al.* (1995) wondered whether foraminiferal tests from the buried peat had been reworked and incorporated into the sediment immediately above, thus biasing the interpretation towards higher elevations. At Meares Island, a layer of tsunami sand blankets the peat over a large area around the section and constitutes evidence that no redeposition from the peat into the overlying mud has taken place. The sand itself contains too few foraminifera to be a source of error-causing redeposition.

Goldstein and Harben (1993) and Patterson *et al.* (1994) have shown that living foraminifera can occur to a depth of 30 cm beneath the tidal marsh surface and that there are variations in the composition of the living and total assemblages with depth. Patterson *et al.* (1994) further found that different zonal schemes could be proposed for cores from their study site at Nanaimo on Vancouver Island (Fig. 1), depending on whether the modern samples included only the uppermost centimeter of sediment, or the first 2 cm of sediment, or more, up to 10 cm. They observed little difference between zones obtained with 7-cm and 10-cm modern samples. We

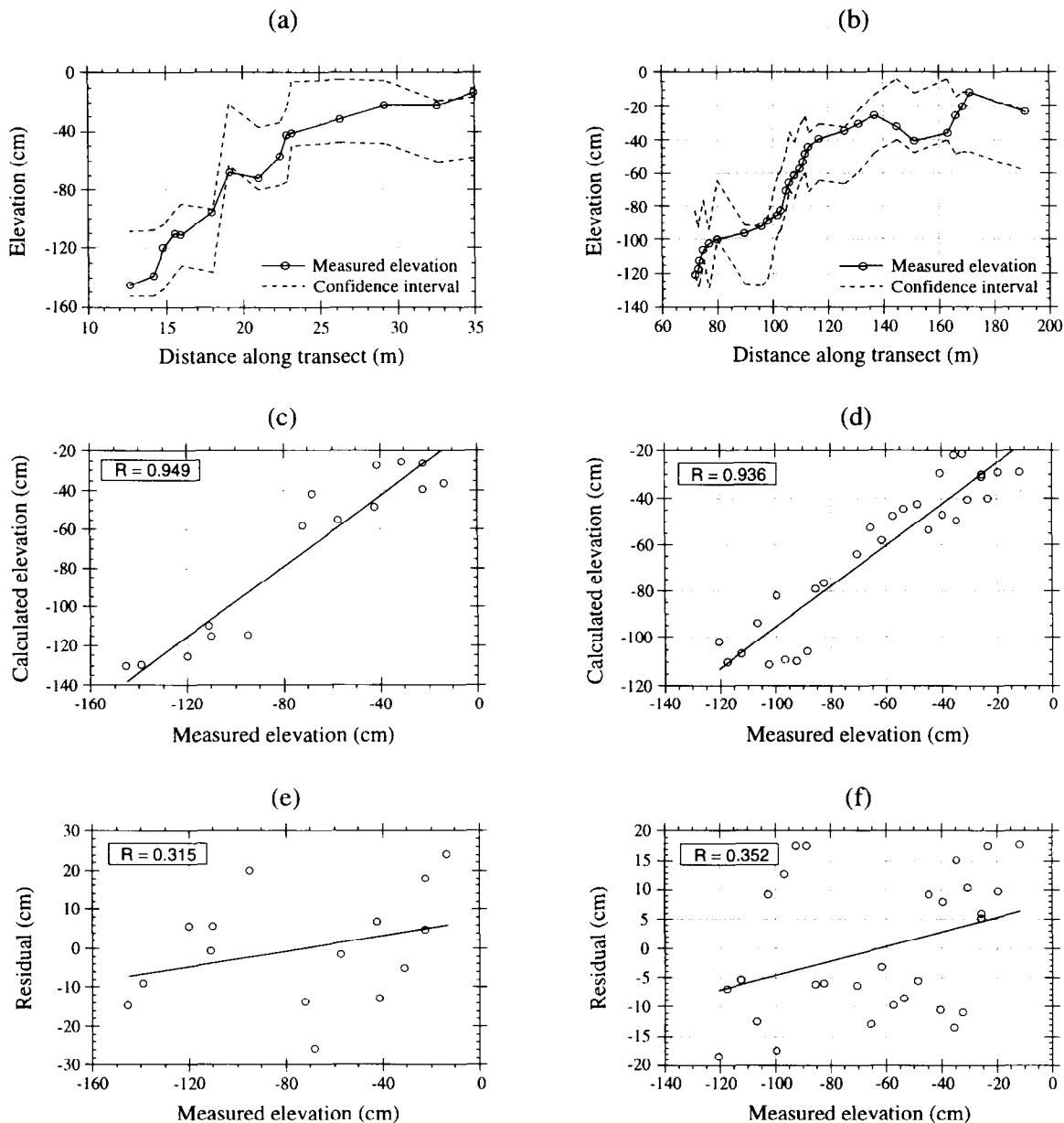


FIG. 9. Graphs showing some of the results of the statistical analysis of the modern data. (a) and (b) Measured sample elevations and envelope of elevations calculated by stepwise regression analysis (80% confidence interval). (c) and (d) Plots of measured vs. calculated elevations. (e) and (f) Plots of residuals (calculated elevations minus measured values) vs. measured elevations. R is the coefficient of correlation. (a), (c) and (e) Cemetery site; (b), (d) and (f) Meares Island site.

sampled only the uppermost 2 cm of sediment, which may introduce a bias. However, it is the opinion of R.T. Patterson (*pers. commun.*, 1995) that, because the greatest density of fauna is found just below the marsh surface, we have enough reliable information at our disposal with a 2-cm sampling depth to estimate paleoelevations, but that adding modern data from greater depths would increase accuracy. Work is now underway to investigate deep infaunal foraminifera at other sites on Vancouver Island where earthquake-induced subsidence has occurred.

Guilbault *et al.* (1995) argued that there has been no significant change in tidal range in the Tofino area in the last several hundred years. Any such change might alter faunal zonation in the marshes. Supporting evidence is the presence of living trees at least 250 years old near the edge of the marsh along the shores of Browning Passage

and the absence of dead trees rooted in the marsh. The presence of old trees shows that upper limit of tides has not been noticeably higher than today since the trees started growing, because they cannot tolerate saltwater. Likewise, the absence of dead trees in the marsh tells us that the sea has not risen from a lower level in the recent past. The rather broad and deep connection between Browning Passage and the open ocean ensures that any increase in tidal prism, and hence salinity, due to coseismic subsidence would be minor. Furthermore, the fact that both sites have comparable foraminiferal distributions as a function of elevation despite the greater exposure of Meares Island to saltwater indicates that the zonation is not particularly sensitive to salinity.

Guilbault *et al.* (1995) concluded that any coseismic compaction would likely be small. The Holocene marsh

TABLE 9. Estimates of coseismic change in relative sea level

	Relative change in sea level (cm)		
	Minimum	Most likely	Maximum
Cemetery (Guilbault <i>et al.</i> , 1995 statistical)	20	57	94
Cemetery (Guilbault <i>et al.</i> , 1995 subjective)	50	68	95
Cemetery (this paper, statistical)	39	71	102
Meares Island (statistical)	29	55	80
Meares Island (subjective)	41	68	84

sequences investigated here are less than 1 m thick and overlie compact glaciomarine clay. In addition, sediment units above the buried marsh display no systematic differences in thickness between sites that are close to bedrock outcrops and those that are farther away (Clague and Bobrowsky, 1994a), which might be expected if the sediment pile compacted significantly during the earthquake.

Guilbault *et al.* (1995) were concerned that some of the coseismic subsidence they attempted to measure was not recorded due to elastic rebound of the Earth's crust soon after the earthquake, before sediment began to accumulate on the subsided marsh surface. To capture as much of the post-seismic rebound as possible, we collected a 1-cm-thick sample of sediment

above the stratigraphic discontinuity (top of buried peat) at the cemetery site and a 0.5-cm-thick sample at the Meares Island site. At the cemetery site, it was not possible to prove that there was no hiatus in sedimentation following the earthquake, although such a hiatus is unlikely. At Meares Island, however, an early resumption of sedimentation is suggested by the presence of an undisturbed layer of tsunami sand on top of the buried peat. Stems and leaves of herbaceous plants rooted in the peat are covered by the sand, indicating that the subsided marsh was not eroded by the tsunami. In addition, a thin layer of sand probably could not remain exposed for long in the intertidal zone, more precisely in the middle marsh, without being washed away.

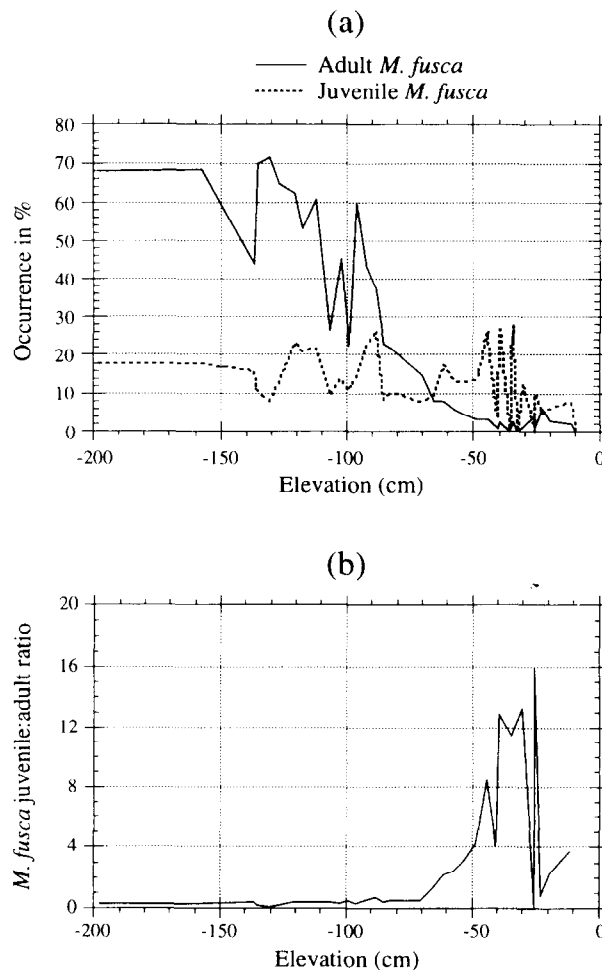


FIG. 10. (a) Vertical distribution of adult and juvenile *Miliammina fusca* (stained + unstained) along the Meares Island transect. (b) Juvenile : adult ratio for *M. fusca* along the Meares Island transect.

Both study sites yield comparable results for the amount of coseismic subsidence (Table 9) and for the period of postseismic rebound (i.e. rebound is largely complete within 6 cm of the top of the buried peat or tsunami sand; Fig. 8). This is strong evidence that the subsidence and post-earthquake recovery are well recorded at these sites.

CONCLUSIONS

Coseismic submergence at the Tofino cemetery site, determined by statistical analysis of foraminiferal data, is estimated to be 71 cm (possible range: 39 to 102 cm). This is comparable to the estimates of Guilbault *et al.* (1995) (most probable value: 57 cm; range: 20 to 94 cm). The estimate of submergence at Meares Island is 55 cm (range: 29 to 80 cm). The differences between the estimates for the two sites are not significant.

The presence of a well preserved layer of tsunami sand above the coseismically subsided marsh surface at the Meares Island site is an indication of good preservation and completeness of the record. Furthermore, the similarity of the post-seismic rebound at both sites (Fig. 8) strongly suggests that there is no hiatus in the sedimentary sequence and that much or all of the rebound is recorded in our samples. Each foraminiferal zone appears to have a similar composition and a similar vertical range over a large area along Browning Passage, and it is unlikely that the tidal prism in this area has changed in the last several hundred years, altering salinity and thus invalidating our paleo-elevation estimates. These facts give us confidence that the estimated coseismic change in relative sea level is reasonable and approximates the amount of coseismic subsidence. The greatest uncertainty stems from the lack of information about deep infaunal foraminifera. We are encouraged by the fact that, at the cemetery section, no *Miliammina fusca* have burrowed from above the stratigraphic discontinuity into the underlying peat. Since *M. fusca* concentrates in the uppermost 2 to 3 cm of sediment in tidal marshes (Patterson *et al.*, 1994), the specimens of that species found just above the discontinuity must have lived there. Thus, the most critical samples for our interpretation would show only minimal bias.

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APPENDIX: TAXONOMIC NOTES

Complementary faunal reference list

Guilbault *et al.* (1995) provided a synonym list for the species they observed at the cemetery site. Most of the species reported in the present paper are the same; the following list includes only species that were not reported by Guilbault *et al.* (1995).

Cribrostomoides jeffreysii (Williamson)

Nonionina jeffreysii Williamson, 1858, p. 34, pl. 3, Figs 72–73.

Alveolophragmium jeffreysii (Williamson). Loeblich and Tappan, 1953, p. 31, pl. 3, Figs 4–7.

Cribrostomoides jeffreysii (Williamson). Murray, 1971, p. 23, pl. 4, Figs 1–5.

Diffflugia globulus (Ehrenberg)

Arcella ? globulus Ehrenberg, 1848, p. 379.

Diffflugia globulus Medioli and Scott, 1983, p. 24, pl. 5, Figs 1–15.

Diffflugia lithophila Penard

Diffflugia lithophila Penard. Ogden and Hedley, 1980, p. 142, pl. 60.

Diffflugia oblonga (Ehrenberg)

Diffflugia oblonga Ehrenberg, 1832, p. 90.

Diffflugia protaeiformis Lamarck

Diffflugia protaeiformis Lamarck, 1816, p. 95.

Diffflugia urceolata Carter

Diffflugia urceolata Carter, 1864, p. 27, pl. 1, Fig. 7.

Elphidium frigidum Cushman

Elphidium frigidum Cushman, 1933, p. 5, pl. 1, Fig. 8.

Elphidium lene (Cushman and McCulloch)

Elphidium incertum (Williamson) var. *lene* Cushman and McCulloch, 1940, p. 170, pl. 19, Figs 2, 4.

Cribronion lene (Cushman and McCulloch). Lankford and Phleger, 1973, p. 118, pl. 3, Fig. 18.

Remark: Our specimens belong to a morphotype of *Elphidium excavatum* (Terquem) which differs from the published morphotypes *clavata*, *excavata*, *selseyensis*, and *lidoensis*. They resemble *Elphidium lene*, which probably also is a morphotype of *Elphidium excavatum*.

Elphidium williamsoni Haynes

Elphidium williamsoni Haynes, 1973, p. 207, pl. 24 Fig. 7, pl. 25 Figs 6, 9, pl. 27 Figs 1–3.

Epistominella vitrea Parker

Epistominella vitrea Parker in Parker *et al.*, 1953, p. 9, pl. 4, Figs 34–36, 40, 41.

Glabratella luxuribulla Patterson

Glabratella luxuribulla Patterson, 1990b, p. 689, Figs 6.6–6.9, 7.1, 7.2.

Haplophragmoides manilaensis Andersen

Haplophragmoides manilaensis Andersen, 1953, p. 21, pl. 4, Fig. 8.

Haplophragmoides bonplandi Todd and Brönniman. Scott and Medioli, 1980, p. 40, pl. 2, Figs 4, 5.

Remarks: Scott *et al.* (1991) suggest that *H. manilaensis* may be synonymous with *Haplophragmoides wilberti*, but we prefer to separate the two until more data are available. Our material resembles the *Haplophragmoides bonplandi* illustrated by Scott and Medioli (1980).

Lagenodifflugia vas (Leidy)

Diffugia vas Leidy, 1874, p. 155.

Lagenodifflugia vas (Leidy). Medioli and Scott, 1983, p. 33, pl. 2, Figs 18–23, 27, 28.

Nebela tubulosa Penard

Nebela tubulosa Penard. Ogden and Hedley, 1980, p. 112, pl. 45.

Pontigulasia compressa (Carter)

Diffugia compressa Carter, 1864, p. 22, pl. 1, Figs 5, 6.

Pontigulasia compressa (Carter). Medioli and Scott, 1983, p. 35, pl. 6, Figs 5–14.

Remaneica helgolandica Rhumbler

Remaneica helgolandica Rhumbler, 1938, p. 194.

Trochammina nana (Brady)

Haplophragmium nana Brady, 1881, p. 50.

Trochammina nana (Brady). Loeblich and Tappan, 1953, p. 50, pl. 8, Fig. 5.0

Remarks on morphotypes

Morphotypes of some of the foraminiferal species were counted separately in the hope that they might have paleoenvironmental significance. *Jadammina macrescens* was counted separately from *Jadammina macrescens* morphotype *polystoma* because the latter seems to prefer more saline settings (Scott and Medioli, 1980; de Rijk, 1995). Large *Haplophragmoides wilberti* with eight or

more fully developed chambers in the last whorl were abundant in one sample near the top of the cemetery transect and thus were counted separately from specimens with fewer chambers. *Siphotrochammina lobata* may be a morphotype of *Trochammina inflata*, but until the two are proven to be synonyms, we will keep them separate. *Trochamminita irregularis*, a variant of *Trochamminita salsa* (Jennings *et al.*, 1995), was also counted separately from the typical morphotype, but only at the Meares Island site. Many, maybe most, of the specimens of *T. salsa* observed by Guilbault *et al.* (1995) at the cemetery site were mistakenly counted as *Jadammina macrescens* morphotype *polystoma*. This is probably one of the reasons for the higher recorded number of *T. salsa* at Meares Island.

Guilbault *et al.* (1995) observed that the upper part of the upper marsh at the cemetery site contained abundant juvenile *Miliammina fusca* and almost no adults, whereas adults were more abundant than juveniles elsewhere in the marsh. This suggests marginal living conditions for that species in the uppermost marsh. Guilbault *et al.* (1995) introduced a '*M. fusca* index' to take into account the variations in the juvenile : adult ratio at the cemetery site. The distinction between juvenile and adult was made on the basis of the length of the test, the boundary being set arbitrarily at 183 μm . At Meares Island, adult and juvenile *M. fusca* were counted separately; adults dominate at lower elevations and decrease rapidly upward, whereas juveniles have a much more regular distribution except near the top of the transect (Fig. 10).

Of these various attempts at separating morphotypes, the only one to give useful results for the paleoenvironmental interpretation was the discrimination between adult and juvenile *Miliammina fusca*. However, all morphotypes that are not specified in the text as having been grouped were kept separate in the statistical analysis.