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EARLY MIOCENE TO QUATERNARY FORAMINIFERA FROM THREE WELLS IN THE QUEEN CHARLOTTE BASIN OFF THE COAST OF BRITISH COLUMBIA

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Forty-two species of benthic and planktic foraminifera were identified from 296 samples from the Murrelet K-15, Harlequin D-86, and Osprey D-36 wells located in the Queen Charlotte Basin. Two distinct temporal and three distinct ecological faunal assemblages were recognizable (Fig. 1). Interpretations, however, were limited by major zones of non-recovery, a sparse foraminiferal fauna, the low number of specimens recovered from each sample, and extensive caving.

In the upper portions of both the Harlequin D-86 and Osprey D-36 wells, a well developed and essentially modern boreal benthic foraminiferal community was identified. The upper portions of these wells are characterized by such neritic (<200 m water depth) species as *Bucella frigida* (Cushman), 1922, *Elphidium excavatum* (Terquem), 1876, *Eouvigerina junciea* (Cushman and Todd), 1941, and *Islandiella limbata* (Cushman and Hughes), 1925. Other taxa characteristic of this neritic interval, although rare, include *Buliminella elegantissima* (d'Orbigny), 1839, *Glabratella ornatissima* (Cushman), 1925, and *Pullenia salisburyi* Stewart and Stewart, 1930. Because all the species found in this zone range from at least the Pliocene and are extant, a biostratigraphic resolution finer than the Pliocene-Quaternary was not possible. The upper zone of the Murrelet K-15 well was virtually devoid of fauna, but tentatively can be interpreted as Pliocene-Quaternary.

The lower faunal zone of the Osprey D-36 well was separated from the upper Pliocene-Quaternary boreal fauna zone by a 640 m hiatus in sampling that occurred between samples 35 (1036-1052 m) and 37 (1687-1697 m). The upper and lower faunal zones identified in the Murrelet K-15 well were separated by a zone of non-recovery spanning over 1700 m. This zone was composed primarily of Upper Miocene and Pliocene nonmarine sandstone and shale. The lower faunal zone identified in the Harlequin D-86 well occurs below the sample 22 level (1006-1021 m) and includes some overlapping Pliocene-Quaternary fauna, possibly due to downhole contamination. Seismic data indicate that the upper and lower faunal zones found in all three wells were separated by two regional unconformities that developed in the Late Miocene and Pliocene (Shouldice, 1971).

The lower faunal zone of the Osprey D-36 well is characterized by an Early Miocene (Saucesian-Relizian Stage) slope fauna which includes the bathyal dwelling (200-1500 m water depth) *Uvigerinella ornata* Cushman, 1926, *Bolivina advena* Cushman, 1925, *Pseudononion costiferum* (Cushman), 1926, and the warm-water dwelling *Siphogenerina transversa* Cushman, 1918. Neritic water depth Miocene faunas, characterized by *Elphidium vulgare* Voloshinova, 1952, were found in the lower faunal zones of both the Murrelet K-15 and Harlequin D-86 wells, which suggests that the basin was more shallow toward the north in the Early to Middle Miocene. The presence of *Bolivina advena* in the Harlequin D-86 well indicates that the lower-fauna bearing sediments of the well were deposited no later than the Middle Miocene (Luisian Stage). The lower-fauna bearing sediments of the Murrelet K-15 well also were most likely deposited during this time as, by the Late Miocene, the site had become inundated by nonmarine sediments.

The Miocene foraminifera from the Harlequin D-86 and Murrelet K-15 wells exhibit extensive diagenesis that is recognizable from the darkened and coarse granular, recystallized tests of the specimens. This phenomenon suggests that there may be a higher degree of thermal and geochemical maturity as one moves northward in the southern Queen Charlotte basin.

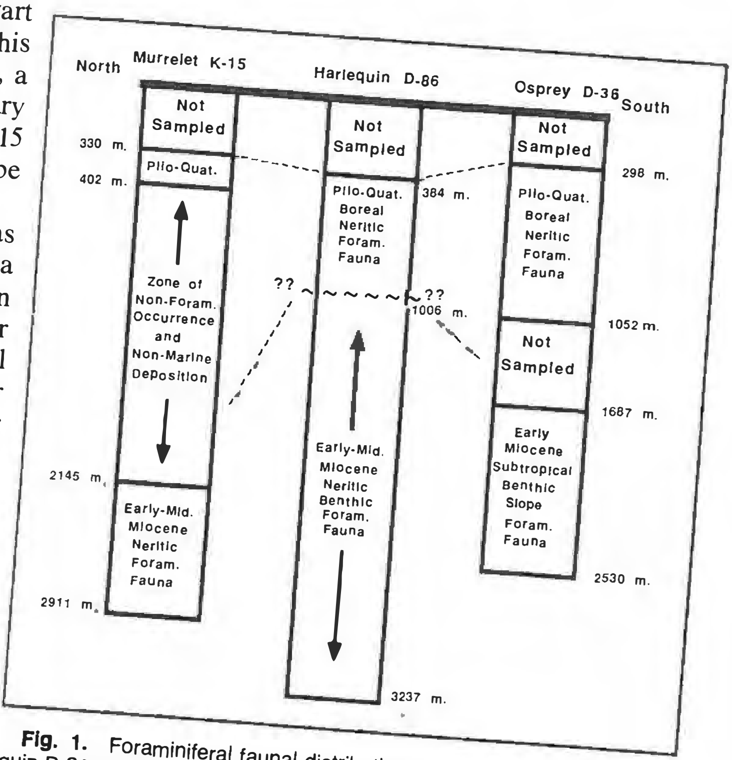

Fig. 1. Foraminiferal faunal distribution in the Osprey D-36, Harlequin D-86, and Murrelet K-15 wells in the Queen Charlotte Basin off the west coast of British Columbia.

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as there are only three frequencies present, when used as a chart for reconstructing paleoelevation this regression curve would yield only three elevation values. The assemblage method of Scott & Medioli (1980) would therefore be most appropriate in analysing such a database. The distributions at Meares Island and Zeballos are much more gradual than presented in the hypothetical example, thus opening the possibility of more detailed reconstruction. When examined at the individual taxa level however, the distributions still exhibits a somewhat patchy distribution (Figure 5). The dense concentrations of points, especially at higher elevations at Zeballos, result from denser sampling, but the empty spaces do not reflect lack of samples so much as patchiness in distribution. Each patch, or cloud of points, might correspond to a biotope, or the patchy distribution might be the result of a natural randomness in foraminifer distribution in these marshes. In this case, additional sampling along the same transect or along a nearby transect in the same marsh might gradually fill the gaps. With the present amount of data, it is not possible to know which scenario is correct. This would be the case in most marshes where determination of paleoelevation based on the distribution of a single species might be attempted. Unless sampling frequency was very high this approach to determining paleoelevation would probably be unreliable. However, when several species are considered together the patchiness becomes greatly reduced. Utilisation of a methodology such as linear regression-based transfer functions to simultaneously analyse distributional data compiled from many species provides the cross-referencing required to obtain paleoelevation results whose confidence intervals and standard errors narrow enough to allow, for example, earthquake subsidence reconstruction (Guilbault *et al.*, 1995, 1996).

CONCLUSIONS

The results of this study show that on the west coast of Canada, the relative frequency of marsh foraminifera correlate very well with elevation. The best correlation is observed with *M. fusca*, followed by *B. pseudomacrescens* and by *T. salsa*. The sum of *B. pseudomacrescens*, *T. salsa* and *J. macrescens* correlates better than each of the three species taken separately. Better results are obtained by sampling the upper 10 cm of sediment than with just the uppermost centimetre. This result confirms prior determinations that a complete picture of a marsh's fauna must take into account the effects of taphonomy and of infaunal habitat. Although the values of R are high, the distribution of points on frequency vs. elevation graphs is patchy, possibly corresponding to biotopes in the marsh. Thus, calculating paleoelevation using the regression curve for a single species is not recommended unless finely subdivided databases are compiled that might - or might not - fill blanks between clouds of foraminiferal distribution data. Alternatively, application of methodologies such as transfer functions permits simultaneous analysis of several species, reducing possible patchiness, and greatly reducing the number of samples required to obtain high resolution results.

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Table 1. Correlation coefficient R for the three sample suites discussed in the text and for various species, variants and groupings. Bold type: correlation coefficients significant to the 99% level; underlined: significant to the 95% level; other correlation coefficients: not significant. There were 35 samples in the Meares Island suite and 36 in both Zeballos suites.

	Meares Island	Zeballos 0-10 cm	Zeballos 0-1 cm
B. pseudomacrescens	–	**0.896**	**0.726**
J. macrescens	–	**0.545**	0.375
B. pseudomacrescens + *J. macrescens*	**0.564**	**0.934**	**0.840**
Trochamminita salsa	**0.705**	0.339	0.246
B. pseudomacrescens + *J. macrescens* + *T. salsa*	**0.845**	**0.936**	**0.843**
Haplophragmoides wilberti	0.387	0.181	0.046
Adult *Miliammina fusca*	**-0.913**	**-0.917**	**-0.839**
Juvenile *Miliammina fusca*	-0.315	-0.393	**-0.870**
total *Miliammina fusca*	**-0.892**	**-0.949**	**-0.883**

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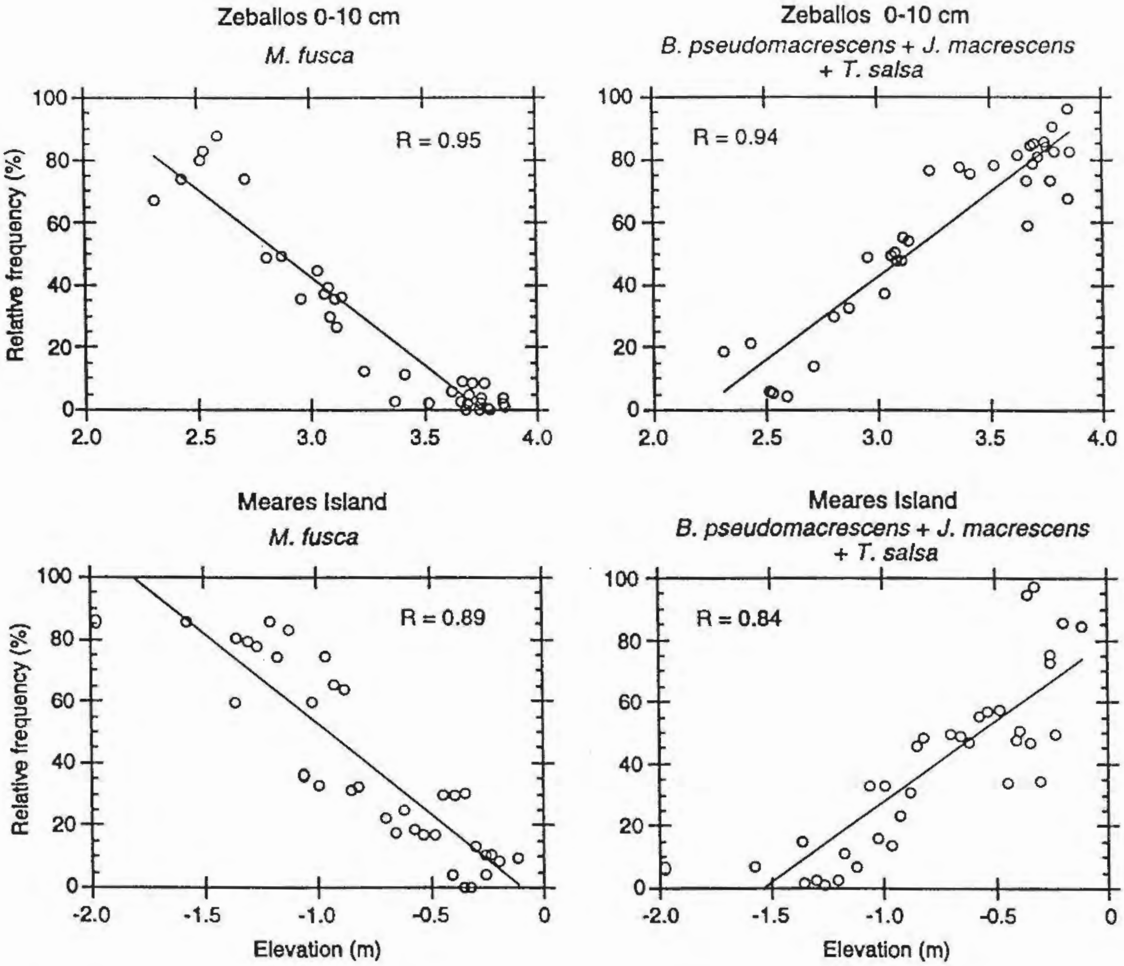

Figure 5. Correlation between elevation and the frequencies of the major foraminiferal species at Zeballos (0-10 cm sample suite) and Meares Island.

DISCUSSION

Differences between shallow and deep samples

The difference in the values of R obtained for the 0-10 cm versus the 0-1 cm sample suites (except for juvenile *M. fusca*) is not surprising in the light of the infaunal depth habitat profiles obtained elsewhere on Vancouver Island, where marsh foraminifera were found living as deeply as 30 cm below the surface, but in different proportions (Ozarko *et al.*, 1997). Furthermore, Patterson *et al.* (1999) have shown that cluster analysis yields a greater number of biofacies with thicker (0-10 cm) surface samples than those collected at 0-1 cm. This is because, at or very near the surface of the marsh, short term (daily, seasonal) environmental variations give rise to a more irregular foraminiferal distribution and consequently low values of R. In addition, thicker surface marsh samples take infaunal habitat and taphonomic processes into account giving values representative of long-term average conditions.

Contrary to the other forms, juvenile *M. fusca* yields higher R values in the 0-1 cm than in the 0-10 cm samples. The most simple explanation for this result is that since *M. fusca* lives predominantly near the surface (Ozarko *et al.*, 1997), the tests found below 1 cm are all dead and therefore adults (since there is no obvious cause for mass mortality). The proportion of juveniles, both dead and living, found in the 0-10 cm samples is too high to fully support this hypothesis but it is probably part of the explanation. This distribution combined with the fact that smaller relative frequencies leads to larger relative errors would also have caused R to diminish.

An alternate explanation would be that adults migrate downward after being born near the surface; once again this is not supported by the observed distribution of live versus dead. It is not impossible that the young undergo some postmortem destruction having not yet developed a coarse agglutination. This would lead to a patchy distribution. However, the *M. fusca* tests we observed were generally well-preserved and did not suggest postmortem damage. A final possibility is that the deeper parts of the cores sample sediment that was deposited at a time of higher relative sea level. We sampled a 60 cm deep section in the upper part of the marsh in a search for such higher paleo sea levels that might have resulted from past earthquakes but found no *M. fusca*-rich assemblages. It would have been astonishing if a *M. fusca*-rich layer dating from a few decades or centuries had been present at all points of the marsh exactly between 1 and 10 cm below the surface.

Because of the important differences that exist between the 0-10 and 0-1 cm suites we think it is necessary to rely only, for interpreting fossil material, on the 0-10 cm data set because it synthesises environmental variations over a longer period of time.

Factors related to elevation

We realise that "elevation", *per se*, is no more of a factor than, for example, water depth for offshore foraminifera. Thus the relationship between elevation and the contained foraminiferal faunas is complex and probably involves many different physiographic parameters including temperature, tidal range, exposure, etc. Some other biologically important factors such as average salinity are probably not good elevation-related factors though. For example, De Rijk (1995a) noted that in Great Marshes, Massachusetts, salinity was not correlated with elevation. Our salinity data are not complete enough to make a regression but if salinity was an important elevation-controlled factor, then *H. wilberti*, known to prefer low salinities (De Rijk, 1995a, b), would show a good positive correlation. Scott & Medioli (1980) concluded that the most significant factor related to elevation is probably "exposure time". This is a broad term under which can be listed the effects of exposure to air, sun, desiccation, rain, freshwater flooding and seepage, wide salinity variations, etc. The impact of these various exposure components will be differently expressed depending on the climate but all cumulatively contribute to clearly distinguishing intertidal ecotone areas from the rest of the marine environment, and they become increasingly important going up the marsh.

Marsh correlation studies elsewhere

Some studies involving linear correlation of faunal frequencies with elevation have been carried out along the eastern seaboard of the United States. These studies report much lower R values than recorded here on the coast of British Columbia. De Rijk (1995a, b) and De Rijk & Troelstra (1997), both in marshes at Cape Cod, Massachusetts, found only one significant correlation with elevation, an R value of -0.67 for *M. fusca*. However, as these studies were carried out in the upper marsh, these lower levels of correlation are expected. In a broader-scale investigation of foraminifera in many marshes along the coast of Maine, Gehrels & Van de Plassche (1999) have found a somewhat higher correlation coefficient (R^2=0.55, R=0.74) for *J. macrescens* but no correlation (R^2=0.03, R=0.17) for *B. pseudomacrescens*. Their research is based on upper marsh data but according to Gehrels (pers. comm.), the correlations are even worse when lower marsh results are included in the data set. The lumping of taxa, as we have done in this study, might have improved their results. There are also numerous environmental differences between the east coast of the USA and the west coast of Canada which may explain the different results obtained in these regions: climate, marsh vegetation, upland vegetation, pH, dissolved oxygen in ground water and the fewer foraminifer taxa in Vancouver Island marshes may all be significant factors. The most significant difference between the regions however is that at Cape Cod, the low oxygen content of the sediment prevents foraminifera from living deeper than 2 cm (De Rijk, 1995a; De Rijk & Troelstra, 1997). In contrast, on Vancouver Island, it is only by including sediments from below 2 cm that we find the assemblages that give the good correlations reported here.

Beyond statistically based research, there have been numerous studies where the correlation between species do not follow the pattern we observe on Vancouver Island. For example, Scott *et al.* (1996) report for Hokkaido, Japan, and northern California distributions of *M. fusca* that bear little relationship with elevation, although in Washington State, close to our working area, they report *M. fusca* to be clearly more frequent in the lower marsh. We cannot supply explanations for these differences. Further research is required to ascertain whether the good correlations reported in this paper are widespread.

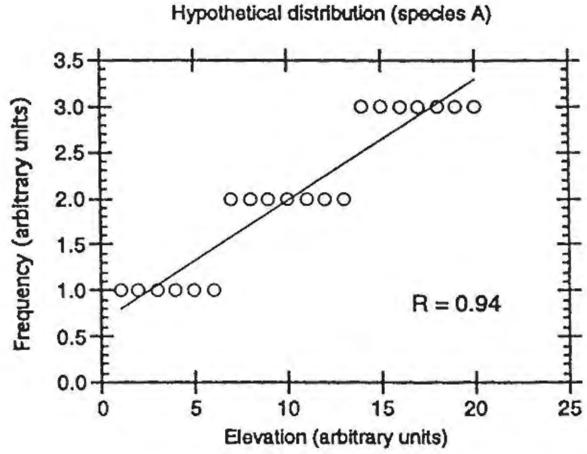

Figure 6. Correlation between elevation and the frequencies for a hypothetical distribution in which species have the same frequency throughout a three-step interval.

Value of linear regression in paleoecology

Good correlation between species frequency and elevation, in particular when R is above 0.9, suggests that paleoelevation might be estimated by knowing only the frequency of a single species. However, a simple experiment shows that without careful assessment of the data these results may be meaningless. Figure 6 shows a hypothetical distribution where species A has only three frequencies; 1 in the lower marsh, 2 in the middle marsh, and 3 in the upper marsh. This species is well-correlated to elevation with a very high R value of 0.94. However,

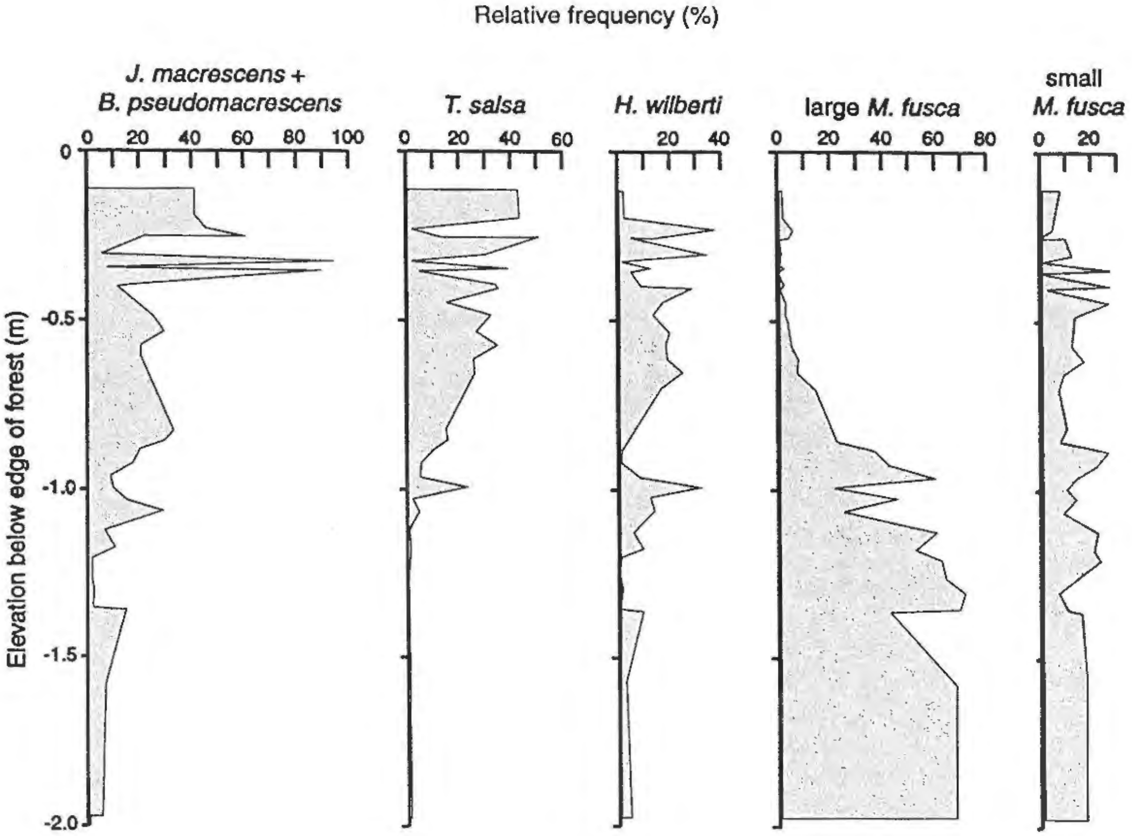

Figure 3. Meares Island distribution. Percentage in function of elevation of the main foraminifer species (living + dead) in the Meares Island marsh. Large (adult) and small (juvenile) specimens are distinguished by an arbitrary test length of 183 μm.

By lumping all three taxa they obtained a much higher value for R of 0.82 (0.85 with the present data set). Table 1 shows that as upper marsh species are gradually lumped, correlation coefficients increase at Zeballos also. It seems obvious that grouping species that tend to occur at higher elevation would yield higher values for R and the aim of the present exercise is in part to verify this. However, contrary to Meares Island where *T. salsa* is abundant and correlates moderately well with elevation (0.71), no correlation at all for this species is observed at Zeballos (0.24). As was the case with *J. macrescens*, this lack of correlation could be the result of the low relative frequencies of *T. salsa* at this site.

Miliammina fusca

The correlation between *M. fusca* and elevation is simpler to determine than the cases described above because it is not necessary to lump the species with other taxa. Adult and total *M. fusca* populations correlate well with elevation both at Meares Island and in the 0-10 cm suite at Zeballos, reaching as high as -0.95. In contrast, juvenile *M. fusca* populations in these suites do not correlate well when analysed alone. The lack of correlation between elevation and juveniles does not impact R values for total *M. fusca* probably because of the number of juveniles is small even in the uppermost parts of the marsh. The observation by Guilbault *et al.* (1995, 1996) at Meares Island that the uppermost marsh contains mostly juvenile *M. fusca* and few adults is confirmed at Zeballos (Figures 3 and 4). This might be explained by adverse conditions, preventing *M. fusca* from living long enough to reach the adult stage (Guilbault *et al.*, 1995). Alternatively, some juvenile specimens appearing at hostile higher elevations may include developmentally arrested adults. We have found that R values for total adult *M. fusca* populations remain around -0.90 or slightly above whether or not arcellaceans are included in the relative frequency calculations, and whether or not tidal flat samples are included in the regression calculation. Contrary to the preceding suites, both adult and juvenile *M. fusca* correlate well with elevation in the 0-1 cm layer at Zeballos, although adults correlate somewhat less well than with the 0-10 cm data (R = -0.84 compared to -0.92 for the 0-10 cm data).

Haplophragmoides wilberti

The low R values obtained for *H. wilberti* (Table 1) probably indicate that ecological parameters other than those related to elevation control their distribution. This is consistent with the results of De Rijk (1995a,b), which showed a clear correlation between *H. wilberti* and salinity, but no correlation with elevation.

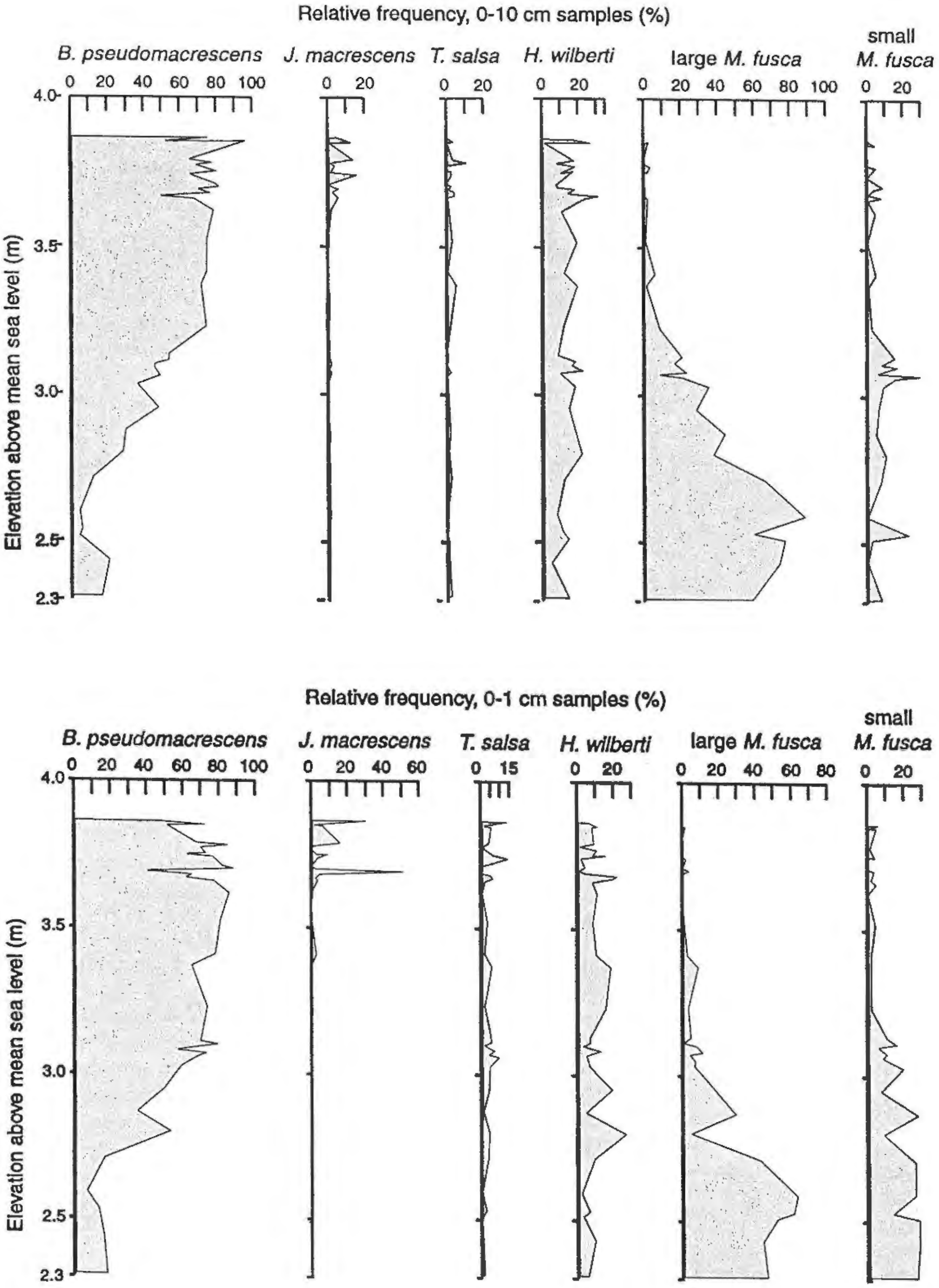

Figure 4. Zeballos distribution. Relative frequency in function of elevation of the main foraminifer species in the Zeballos marsh, between the surface and 10 cm depth (top) and between surface and 1 cm depth (bottom).

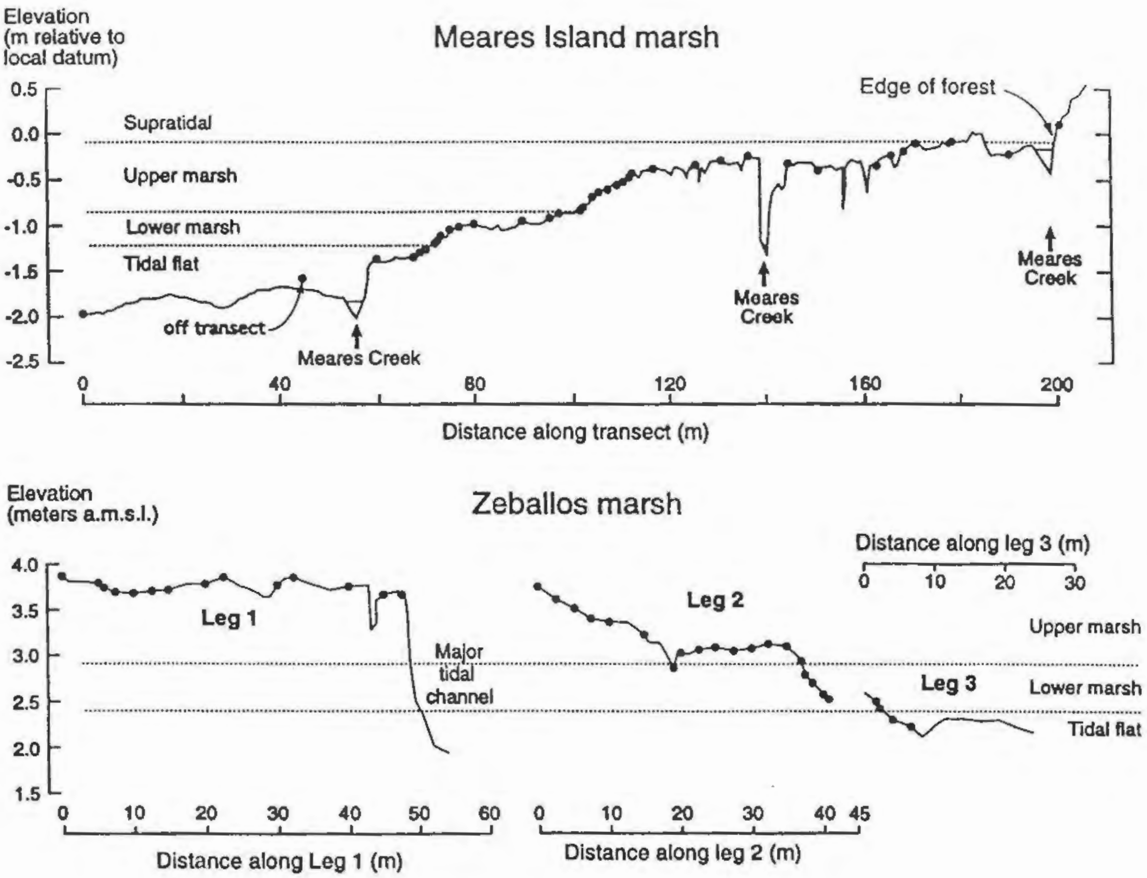

Figure 2. Elevation profiles of the Meares Island and Zeballos marshes. Dots represent sampling points. The local datum at Meares Island is the edge of the forest and at Zeballos, mean sea level. At Zeballos, Leg 2 is roughly perpendicular to Leg 1 whereas Leg 3 is parallel to Leg 2. At both sites, the limit between upper marsh and lower marsh is set at the point where *M. fusca* becomes more abundant than the sum of *B. pseudomacrescens*, *J. macrescens* and *T. salsa*.

Care was taken during sampling that only minimal elevation gaps were left between each station. At Zeballos, salinity measurements of 3-8‰ were obtained using a temperature-compensated refractometer. These low salinity values are the result of Zeballos being situated at the head of a 27 km long inlet with a sizable river flowing into the sea adjacent to the marsh. Further evidence of low salinity was provided by dwarfed populations (individuals only reaching about 3 cm in length) of the bivalve *Mytilus edulis* on the Zeballos tidal flat (for the relationship between *M. edulis* shell length and salinity, see Zenkevitch, 1963, p. 310). No direct salinity measurements were taken at Meares Island. However, as that site is only 5 km away from the inlet's broad connection to the open sea, and as the only input of freshwater locally is a small creek crossing the marsh, it is more exposed than Zeballos to marine influence. Although the small creek flows through the marsh near the study site, its influence is limited to adjacent low areas, as indicated by increased proportions of freshwater arcellaceans.

MATERIAL AND METHODS

Thirty-seven samples were collected and analysed at Meares Island and 38 at Zeballos. Elevations relative to a local datum (± 1 cm) were obtained using a surveyor's level. Samples were collected with a garden bulb planter used as a coring device. At Meares Island, the top 2 to 3 cm of sediment was collected. At Zeballos, 10 cm thick surface samples were taken. The Zeballos samples were in turn split longitudinally to provide material for separate analysis of the 0-10 cm and the 0-1 cm intervals. Ozarko *et al.* (1997) found that surface samples comprising the top ten centimetres provided a more reliable indication of biofacies or ecozones than shallower samples when used to interpret fossil successions, because the effects of infaunal habitat and taphonomy were taken into consideration. In addition, Patterson *et al.* (1999) have shown that in the case of the Zeballos material discussed here, cluster analysis provides a greater elevational resolution with the 0-10 cm than with the 0-1 cm suite.

Samples were screened through a 63 µm sieve and split with a wet sample splitter (Scott & Hermelin, 1993) until at least a minimal statistically valid fraction was obtained. Samples were examined "wet" with a binocular microscope, usually at 50x magnification.

Statistical Approach

A statistically valid number of foraminifer specimens were counted based on the approach of Patterson & Fishbein (1989). We accepted a species occurrence as statistically significant if its frequency was equal to the standard error +1% at the 95% confidence level; in a tidal marsh, where percentages of indicator species are high, this may involve counting much less than the usual 300 specimens per sample. Two of the Meares Island samples were removed from consideration because they were from freshwater environments and contained too few specimens. Two other samples collected from depressions at the Zeballos site were also discarded from the data set because they were composed of faunal material flushed in by the tide. Thirty-five samples from Meares Island and 36 from Zeballos thus constitute the data base for this study.

The Pearson correlation coefficients (R) were determined by plotting the relative frequencies of each of the main species as a function of elevation for both the Zeballos and Meares Island data. Stations from the two sites could not be plotted together because of the differences in local tidal range and marsh height. A linear regression was carried out on the resultant data using the program KaleidaGraph v. 3.0 on an Apple Macintosh computer.

TAXONOMIC REMARKS

At the time that Guilbault *et al.* (1995, 1996) analysed the Meares Island material, they did not distinguish between *Balticammina pseudomacrescens* Brönniman, Lutze & Whittaker and *Jadammina macrescens* (Brady). Both species were then listed together as *J. macrescens*. At Zeballos however, both species were properly distinguished. As a consequence, direct comparison between the distribution of these two species at both sites can be made only by considering their sum. Following Scott & Medioli (1980), we consider *Jadammina polystoma* Bartenstein & Brand to be a morphotype of *J. macrescens*.

Jennings *et al.* (1995) reported a continuous gradation between *Trochamminita salsa* (Cushman & Brönniman) and *Trochamminita irregularis* Cushman & Brönniman. We thus consider *T. irregularis* to be a morphotype of *T. salsa*. The *T. irregularis* morphotype was common at Meares Island but absent at Zeballos. Young and adult *Miliammina fusca* (Brady) were counted separately, as Guilbault *et al.* (1996) reported that juveniles at Meares Island do not correlate with elevation. Like these authors we use an arbitrary test length of 183 μm to discriminate juveniles from adults.

Due to low abundances or localised occurrences, some taxa were not included in our analyses. Only a few specimens of the halophilic species *Trochammina inflata* (Montagu) were observed at Zeballos, probably due to the very depressed salinity (Patterson, 1990). *Pseudothurammina limnetis* (Scott & Medioli) occurred only in some uppermost marsh samples and did not exhibit a gradual, linear correlation with elevation. Finally, *Polysaccammina ipohalina* Scott and *Polysaccammina hyperhalina* Medioli, Scott & Petrucci were present at Meares Island but entirely absent from the Zeballos site.

RESULTS

Tables with raw data for Meares Island can be found in Guilbault *et al.* (1996) and for Zeballos in Patterson *et al.* (1999). Graphs showing the distributions of the main species at both sites as a function of elevation can be found in Figures 3 and 4. Correlations were computed for three surface sample suites: Meares Island (0-3 cm), Zeballos (0-1 cm), and Zeballos (0-10 cm). Correlation coefficients (R) were also calculated for the following species: *M. fusca*, both juvenile and adult, *B. pseudomacrescens*, *J. macrescens*, *T. salsa*, and *Haplophragmoides wilberti* Andersen. Examples of linear regression graphs are shown on Figure 5.

Elevation related R values for the various species and data sets are provided in Table 1. All correlations are based on the percentage of foraminifera recorded, excluding freshwater arcellaceans. Arcellaceans bear no relation to elevation within these marshes; although many are found living in marshes, a large number are probably reworked from upland areas during occasional floods. The values of R given for Meares Island differ slightly from those published for the same sample set by Guilbault *et al.* (1996), because five of the six tidal flat samples were then excluded from that data set whereas all are included here. The level of significance of the correlation values (95% or 99% level) is also given in Table 1. For 30 samples, correlation coefficients of $R \geq 0.361$ are 95% significant and $R \geq 0.463$ are 99% significant.

B. pseudomacrescens, *J. macrescens* and *T. salsa*

We found the correlation between elevation and the relative frequency of *J. macrescens* at Zeballos to be low (0.55) for 0-10 cm and even lower (0.37) for 0-1 cm. The poor correlation could result from the low representation of the species at the Zeballos site and the resultant associated high relative errors. In contrast, the R value for *B. pseudomacrescens* at Zeballos is moderate (0.73) in the surficial layer and high (0.90) for the 0-10 cm surface samples. When both *J. macrescens* and *B. pseudomacrescens* are lumped, the values for R increase to 0.84 (0-1 cm) and 0.93 (0-10 cm) respectively.

At Meares Island though, the correlation between elevation and the sum of *B. pseudomacrescens* and *J. macrescens* is low (0.56). However, Guilbault *et al.* (1996) noted that the low percentages of *J. macrescens*, inclusive of *B. pseudomacrescens*, tended to coincide with high percentages of *T. salsa* because the upper marsh was mostly populated by varying numbers of these two species.