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Foraminiferal Evidence of Younger Dryas Age Cooling on the British Columbia Shelf

Indications foraminiférologiques d’un refroidissement du Dryas récent sur la plate-forme de la Colombie-Britannique

Foraminiferen-Belege über die Abktühlung in der jüngeren Dryaszeit auf der Terrasse von British Columbia

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Article abstract

Cluster analysis of foraminifera from a ~12,000-9000 radiocarbon year old piston core from Goose Island Trough, Queen Charlotte Sound, indicates that a cold interval correlative with the Younger Dryas stadial occurred during a shallow water phase. The reduction in depth was caused by the passage across the area, between 11,500 and 10,000 years BP, of a glacial forebulge associated with the retreat of the Late Wisconsinian ice sheets. Published sedimentological evidence indicate that water depths decreased to ~75-90 m, placing the site above the permanent North Pacific pycnocline (100 m). Low salinity-near glacial conditions, at these depths, between -11,100 and 10,000 years BP were recognized by abundant populations of Cassidulina reniforme and lslandiella helenae. This cold interval has also been recognized in cores from elsewhere in Queen Charlotte Sound. The depressed salinity and temperature may have resulted from a modification of regional weather patterns. Decreased mean continental summer temperatures could have reduced the seasonal influence of the North Pacific High and lengthened that of the Aleutian Low. This would have resulted in a near continuous onshore surface Ekman transport and enhanced coastal runoff, effectively blocking the movement onto the shelf of deep, saline, warm water of the California Undercurrent. The resultant isolated inshore basin comprised of present-day Hecate Strait and Queen Charlotte Sound is tentatively named the "Hecate Sea". By ~10,000 years BP, weather and ocean circulation had returned to near modern patterns as indicated by the disappearance of lslandiella helenae and by the development of an Epistominella vitrea - dominated biofacies.

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FORAMINIFERAL EVIDENCE OF YOUNGER DRYAS AGE COOLING ON THE BRITISH COLUMBIA SHELF

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ABSTRACT *Foraminiferal evidence of Younger Dryas age cooling on the British Columbia shelf.* Cluster analysis of foraminifera from a ~12,000-9000 radiocarbon year old piston core from Goose Island Trough, Queen Charlotte Sound, indicates that a cold interval correlative with the Younger Dryas stadial occurred during a shallow water phase. The reduction in depth was caused by the passage across the area, between 11,500 and 10,000 years BP, of a glacial forebulge associated with the retreat of the Late Wisconsinian ice sheets. Published sedimentological evidence indicate that water depths decreased to ~75-90 m, placing the site above the permanent North Pacific pycnocline (100 m). Low salinity-near glacial conditions, at these depths, between ~11,100 and 10,000 years BP were recognized by abundant populations of *Cassidulina reniforme* and *Islandiella helenae*. This cold interval has also been recognized in cores from elsewhere in Queen Charlotte Sound. The depressed salinity and temperature may have resulted from a modification of regional weather patterns. Decreased mean continental summer temperatures could have reduced the seasonal influence of the North Pacific High and lengthened that of the Aleutian Low. This would have resulted in a near continuous onshore surface Ekman transport and enhanced coastal runoff, effectively blocking the movement onto the shelf of deep, saline, warm water of the California Undercurrent. The resultant isolated inshore basin comprised of present-day Hecate Strait and Queen Charlotte Sound is tentatively named the "Hecate Sea". By ~10,000 years BP, weather and ocean circulation had returned to near modern patterns as indicated by the disappearance of *Islandiella helenae* and by the development of an *Epistominella vitrea* - dominated biofacies.

RÉSUMÉ *Indications foraminiférologiques d'un refroidissement du Dryas récent sur la plate-forme de la Colombie-Britannique.* L'analyse des groupements effectuée sur des populations de foraminifères d'une carotte à piston couvrant la période de 12 000 à 9000 ans BP, provenant du Goose Island Trough, dans le bassin de la Reine-Charlotte, démontre l'existence d'un intervalle froid contemporain du Dryas récent. Il coïncide avec une phase à bathymétrie réduite qui résulte du déplacement vers l'est, entre 11 500 et 10 000 ans BP, du bombement isostatique associé à l'Inlandsis de la Cordillière à la suite de son retrait. Des données sédimentologiques publiées montrent que la profondeur a diminué jusqu'à ~75-90 m, amenant le site étudié au-dessus de la pycnocline permanente du Pacifique Nord (100 m). L'existence de conditions hyposalines de type glaciaire, à ces profondeurs, entre 11 100 et 10 000 ans BP ont été reconnues grâce à la présence d'assemblages à *Cassidulina reniforme* et *Islandiella helenae*. Cet intervalle froid a également été reconnu ailleurs dans le bassin de la Reine-Charlotte. Les salinités et les températures réduites sont peut-être le résultat d'un changement dans les configurations météorologiques régionales. Des températures estivales plus basses sur le continent auraient réduit l'influence saisonnière de l'anticyclone du Pacifique Nord et rallongé celle de la dépression des Aléoutiennes. Ceci aurait engendré un transport d'Ekman de surface quasi permanent vers la côte et provoqué une augmentation des précipitations, ayant eu pour effet de bloquer la remontée des eaux salées et tièdes du sous-courant de Californie. Nous proposons d'appeler « Mer d'Hécate » le bassin côtier ainsi créé comprenant l'actuel détroit d'Hécate et le bassin de la Reine-Charlotte. Dès avant ~10 000 ans BP, les circulations atmosphérique et océanique étaient revenues à une configuration presque moderne.

ZUSAMMENFASSUNG *Foraminiferen-Belege über die Abktühlung in der jüngeren Dryaszeit auf der Terrasse von British Columbia.* Die Analyse der Foraminiferen-Anhäufungen von einem ~12,000-9000 Radiokarbonjahre alten Bohrkern von Goose Island Trough im Queen Charlotte Sund zeigt, daß ein kaltes Intervall gleichzeitig mit dem jüngeren Dryas-Stadium während einer Phase seichten Wassers eintrat. Die Verringerung der Tiefe wurde durch die Passage einer glazialen Emporwölbung zwischen 11,500 und 10,000 Jahren v.u.Z. quer durch das Gebiet bewirkt, zusammen mit dem Rückzug der Eisdecken vom späten Wisconsinium. Die veröfentlichten sedimentologischen Belege zeigen, daß die Wassertiefen auf ~75-90 m abnahmen, und so den Platz über die ständige Dichte-Gradient des Nordpazifik (100 m)stellten.Fast glaziale Bedingungen mit niedrigem Salzgehalt wurden in diesen Tiefen zwischen ~11,100 und 10,000 Jahren v.u.Z. auf Grund von reichlichen Populationen von *Cassidulina reniforme* und *Islandiella helenae* erkannt. Der verringerte Salzgehalt und die niedrigere Temperatur könnten auch durch eine Änderung der regionalen Wetterkonstellationen bewirkt worden sein. Gesunkene durchschnittliche kontinentale Sommertemperaturen könnten den jahres-zeitlichen Einfluß des nordpazifischen Hochs verringert und den des atlantischen Tiefs verlängert haben. Das könnte einen fast kontinuierlichen Ekman-Transport an der Oberfläche zur Küste hin bewirkt und die Küsten-Niederschläge verstärkt haben, und so wäre die Bewegung von tiefem, salzhaltigem warmem Wasser der kaliforni-schen Unterströmung zur Terrasse hin blockiert worden. Das daraus resultierende isolierte Binnen-Becken, bestehend aus der heutigen Hecate-Meerenge und dem Queen Charlotte Sund, wird probeweise "Hecate Sea" genannt. Um ~10,000 Jahre v.u.Z. sind Wetter und Ozeanströmung zu nahezu modernen Mustern zurückgekehrt.

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INTRODUCTION

In recent years, concern over the ramifications of global change — both cooling and warming — has resulted in a dramatic increase in the number of studies concerned with past climatic oscillations. These paleoclimatic and paleoceanographic studies are necessary to adequately assess the nature of environmental changes that may be occurring today. From a Canadian perspective, an understanding of past oceanographic and climatic change is critical, as climate models predict that global changes will most profoundly influence higher latitude areas. As the late Quaternary-Holocene paleoceanographic evolution of coastal British Columbia is almost unknown, it is particularly important that such studies be implemented there (Fig. 1).

There has been considerable study of the Younger Dryas cold stadial in northern Europe as a reflection of dramatic and rapid climatic oscillations (Lehman, 1993; Rutter, 1993). Accumulating evidence suggests that the cooling associated with the Younger Dryas was not an exclusively northern European event. During the 1980's evidence from eastern North America indicated that cooling was experienced throughout the entire North Atlantic region and several models were presented to explain the phenomenon (Rooth, 1982; Mott *et al.*, 1986; Broecker *et al.*, 1988, 1989; Wright, 1989). Researchers have also found evidence of Younger Dryas type cooling at many localities outside the North Atlantic region (*e.g.*, Rind *et al.*, 1986; Engstrom *et al.*, 1990; Reasoner *et al.*, 1993; Hebda, 1993; Alley, 1993). Two independent paleoclimatic records using terrestrial pollen and marine foraminifera from the Queen Charlotte Islands and Queen Charlotte Sound, British Columbia (Mathewes *et al.*, 1993; Patterson, 1993) indicate cooling between ~11,300 and 10,100 radiocarbon years before present (BP). Unless they represent contemporary but unrelated events, these results suggest that hemispheric, or global driving mechanisms may be responsible for the Younger Dryas stadial.

The currently favored model to explain development of the Younger Dryas stadial revolves around natural oscillations in the salinity budget of the Atlantic Ocean (Broecker *et al.*, 1990). Unfortunately, this model does not adequately explain the existence of Younger Dryas-like conditions in the northeastern Pacific. Other research (Bond *et al.*, 1993) has suggested that the terminations of the Younger Dryas and of earlier Wisconsinan cold phases were associated with Heinrich events. Heinrich events are postulated to result from catastrophic iceberg calving; the rapid dissemination of icebergs would result in the observed thin ice-rafted deposits throughout the North Atlantic. According to Blanchon and Shaw (1995), such events could have caused sudden global sea-level rises of several metres in amplitude and reduced the elevation of the Laurentide Ice Sheet; as a result, the whole Northern Hemisphere would have undergone drastic warming. Eventually, increased snow accumulation rates would have allowed the ice sheet to return to its earlier elevation, thus bringing about a new cold phase.

Patterson (1993) carried out a foraminiferal analysis of five cores from the Queen Charlotte Sound area of British Columbia. Based on peak occurrences of the cold water indicator *Cassidulina reniforme* in these cores between ≈ 11,000 to 10,000 years BP, he suggested that this shelf-wide cool interval may represent the Younger Dryas cold phase. As the study by Patterson (1993) was of a reconnaissance nature, a more detailed micropaleontological analysis spanning the Younger Dryas isochronous event is required to ascertain the paleoceanographic effects on the region. In this study, high resolution analysis of benthic foraminifera from a single core is carried out to reconstruct paleoceanographic changes in coastal British Columbia during the late Quaternary. A 10 m-long piston core (END 84B-10) was chosen for detailed study as it provides a long and complete sedimentary record and spans the time interval of interest (~12,000-9000 years BP).

LITHOLOGIC SUMMARY

Core END 84B-10 is ideal for paleoceanographic analysis as it has also been studied sedimentologically in conjunction with a large number of other cores from Queen Charlotte Sound and Hecate Strait, and well-located within the regional seismo-stratigraphic framework (Luternauer *et al.*, 1989b). Several lithologies have been recognized which can be found throughout the region (Fig. 2). Lithofacies Unit A, a dark gray massive mud (core END 84B-10 did not reach this unit), was deposited in the presence of an ice front on the continental shelf and is characterized by numerous dropstones. This phase of deglaciation terminated by about 12,200 years BP. Lithofacies Unit B_1 is lithologically similar to Unit A but lacks the dropstones. When this unit was deposited the glaciers had retreated into the fjords.

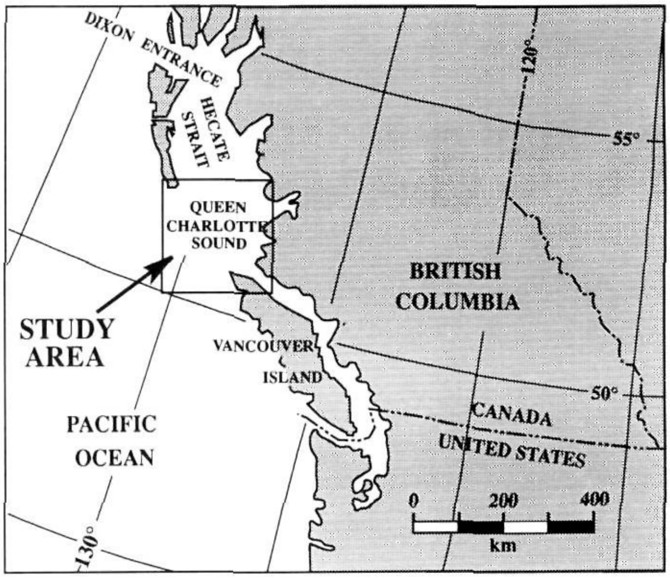


FIGURE 1. Map of western North America showing position of Queen Charlotte Sound.

Carte de l'ouest de l'Amérique du Nord montrant la localisation du bassin de la Reine-Charlotte.

This unit is capped by the shelly sandy muds of Lithofacies Unit B_2. These maximum lowstand deposits were diachronously deposited between 11,600-10,000 years BP as a glacial forebulge migrated across the region. Lithologic Unit B_3 overlays Unit B_2 and is comprised of massive gray muds very similar to those of Unit B_1. Deposition of this unit had terminated everywhere by 9000 years BP. The succession is topped by Lithologic Unit C. Highly variable in thickness, this olive-colored mud is the surface unit over much of the region.

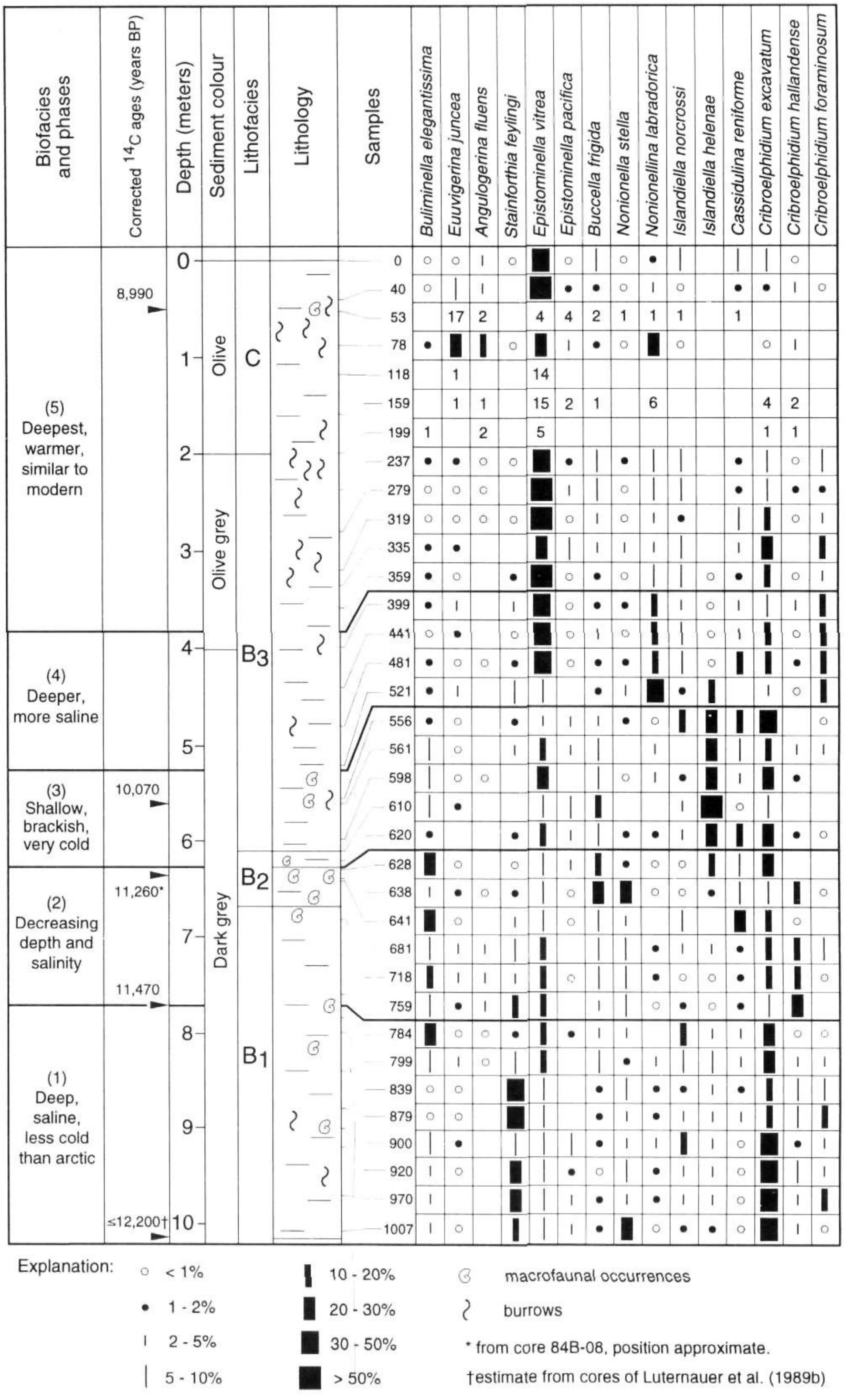


FIGURE 2. Stratigraphic section of core END 84B-10 showing lithology, radiocarbon dates, for-aminiferal biofacies and the distribution of key indicator species. For samples with less than statistically significant number of specimens, the number of specimens recorded is entered instead of percentage symbols. (*) – Correlated date from nearby core END 84B-08. (†) – Luternauer *et al.* (1989b) report that B_1 Unit sediments in Queen Charlotte Sound are no older than 12,200 years BP (age corrected for reservoir effect by Mathewes *et al.*, 1993; Patterson, 1993).

Coupe stratigraphique de la carotte END 84B-10 montrant lithologie, âges au ^{14}C, biofaciès à foraminifères et distribution d'espèces indicatrices. Pour les échantillons dont le nombre de spécimens n'est pas statistiquement significatif, les symboles de pourcentage sont remplacés par le nombre de spécimens observés. (*) – Âge au ^{14}C corrélatif provenant de la carotte voisine END 84B-08. (†) – Luternauer et al. *(1989b) rapportent que les sédiments de l'unité B_1 dans le bassin de la Reine-Charlotte ne sont pas plus anciens que 12 200 ans BP (âge corrigé pour l'effet de réservoir par Mathewes et al., 1993 ; Patterson, 1993).*

METHODS AND MATERIALS

Thirty-five samples were obtained from Geological Survey of Canada piston core END 84B-10, collected at the head of Goose Island Trough (Fig. 3) at 184 m water depth. Sampling points are shown in Figure 2 and Appendix 1. Samples usually represented 3 cm of stratigraphic thickness, but occasionally as little as 1 cm or as much as 5 cm. They were processed by the method described by Patterson and Cameron (1991). Thirty-one samples (Appendix 1) contained enough foraminifers for statistical analysis (see Patterson and Fishbein, 1989).

Eighty-eight species of benthic foraminifera were identified; they are listed in Appendix 2. Planktic foraminifera were counted in 23 samples. They are not abundant in these shelf samples so they were tallied as percentages of total foraminifera but not identified to species level. The percent error was calculated using the standard error equation (s_{x_i}):

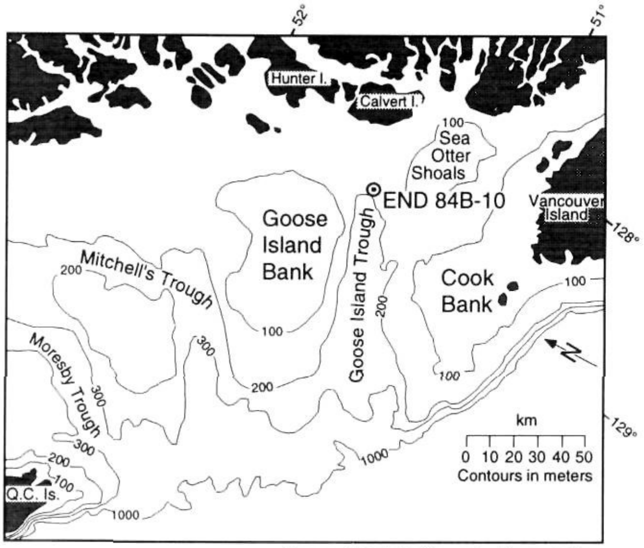
$$s_{x_i} = 1.96 \sqrt{\left[\frac{X_i[1-X_i]}{N} \right]}$$

where N is the total number of specimens in a sample, and X_i is the proportion (expressed in decimal form, not percentage) of a given species (Patterson and Fishbein, 1989). Due to the large matrix generated for this study it was not possible to include error data for all species. The percent error calculated for the 25 species found in statistically significant numbers in at least one sample are included in Appendix 1.

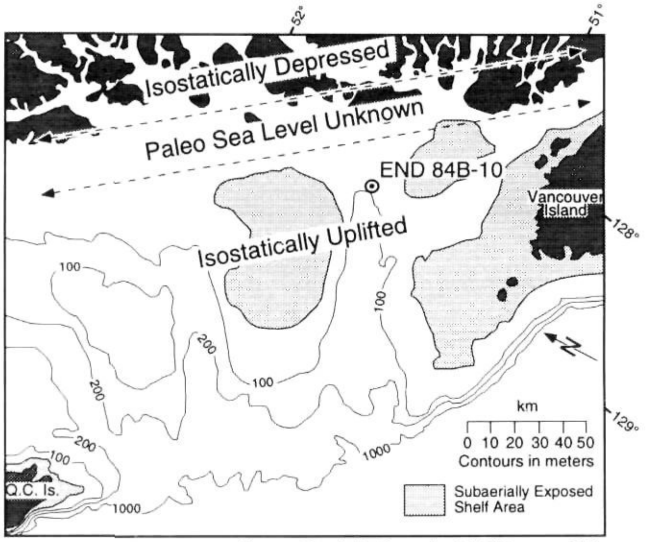
Q-mode cluster analysis was carried out using a technique that has been demonstrated to closely emulate the results of a statistically significant "error-weighed maximum likelihood" clustering method (Fishbein and Patterson, 1993). This method requires that only species present in statistically significant populations be analyzed. It was applied to the twenty-five statistically significant species using SYSTAT (v. 5.2; SYSTAT, Inc. 1992). Euclidean distance correlation coefficients were used to measure similarity between pairs of species, and Ward's linkage method was utilized to arrange sample pairs and sample groups into a hierarchic dendrogram (Fig. 4).

Weighted faunal distribution graphs were generated for the main species, number of species, number of temperate species, percent planktic foraminifera, percent temperate species, and Shannon Diversity Index, to correct for local variations in fractional abundances due to such factors as selective dissolution and post-mortem transport (Fig. 5). The curve is fitted to each plot using the "locally weighted least squared error method" using the computer program KaleidaGraph (v. 2.1; Abelbeck Software, 1990). The resultant best fit smooth curve passes through the center of the data. This is an extremely robust method and unlike the "standard least squared method" is nearly insensitive to outliers. The smoothing procedure examines an arbitrarily selected fraction of the data populations (0.33 here) for each point on the curve: this determines the smoothness of the curve. We could have considered a larger fraction (*e.g.*, 0.66 or 1) but the resultant plots would have missed too much detail.

In this paper, reference is made to 4 accelerator mass spectrometry (AMS) radiocarbon datings (Table I) originally published by Luternauer *et al.* (1989b). The ages have been corrected for reservoir effect (–730 yr.) by Mathewes *et al.* (1993) using the wood/shell pair data of Southon *et al.* (1990). Corrected values are used throughout the text and in Figure 2.



Queen Charlotte Sound – Present Day



Queen Charlotte Sound – 11,000 years B P

FIGURE 3. A. Bathymetric map of Queen Charlotte Sound showing location of core END 84B-10. B. Paleobathymetric map showing location of core END 84B-10 with respect to isostatically uplifted parts of the shelf in the Late Glacial.

A. Carte bathymétrique du bassin de la Reine-Charlotte montrant le site de la carotte END 84B-10. B. Carte paléobathymétrique montrant la position de la carotte END 84B-10 par rapport aux parties de la plate-forme continentale soulevées par isostasie au tardiglaciaire.

RESULTS

BIOFACIES DESCRIPTIONS

Five biofacies can be defined based on Q-mode cluster analysis and direct examination of the data. These biofacies correspond to five distinct stratigraphic intervals, with the exception of three anomalous samples. The samples collected at 53 cm, 118 cm, 159 cm, and 199 cm were excluded from clustering because they contained statistically insignificant foraminiferal populations (Patterson and Fishbein, 1989). The weighted faunal distribution graphs in Figure 5 highlight the relative abundance of selected species throughout the core.

The *Cribroelphidium excavatum - Stainforthia feylingi* Biofacies (1) is dominated by *Cribroelphidium excavatum* (13-40%) and *Stainforthia feylingi* (1-41%)(for a discussion of the taxonomic problems associated with this species, see Knudsen and Seidenkrantz, 1994). Samples of this biofacies also contain variable but occasionally high proportion of *Nonionella stella* (up to 21%), *Islandiella norcrossi* (up to 12%) and *Cribroelphidium foraminosum* (up to 12%). *Epistominella vitrea* is moderately abundant (6-18%). *Buliminella elegantissima, Islandiella helenae* and *Cribroelphidium hallandense* are common but never abundant (always less than 8% except for one 21% occurrence of *Buliminella elegantissima* at 784 cm). The presence of high proportions of *Stainforthia feylingi* in two samples, 839 cm and 879 cm, caused them to cluster distinctly. They have been included in Biofacies 1 as this light, very easily winnowed species is often anomalously concentrated (Collison, 1980, listed as *Stainforthia schreibersiana*; Guilbault, 1993, listed as *Virgulina schreibersiana*). *Nonionella stella* and *Stainforthia feylingi*, are most abundant in Biofacies 1, extend into Biofacies 2 and decline abruptly thereafter.

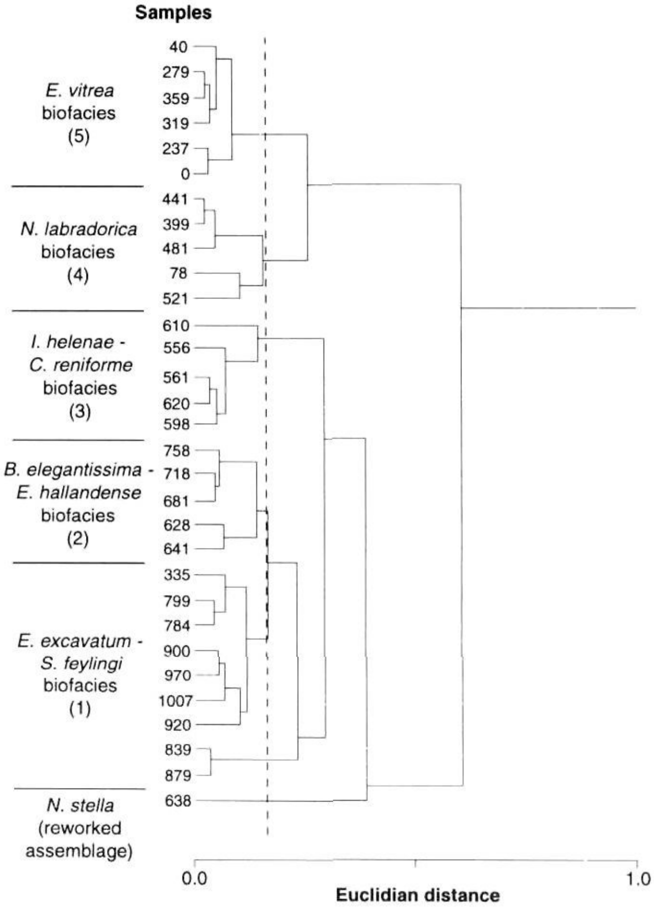


FIGURE 4. Q-Mode dendrogram showing the 31 samples with statistically significant number of specimens from the Late Glacial core END 84B-10. Clusters of samples with correlation coefficients greater than the level indicated by the dashed line were considered biofacies.

Dendrogramme en mode Q montrant les 31 échantillons de la carotte tardiglaciaire END 84B-10 dont le nombre de spécimens est statistiquement significatif. Les groupements d'échantillons dont les coefficients de corrélation sont supérieurs au niveau indiqué par la ligne tiretée sont considérés comme étant des biofaciès.

The *Buliminella elegantissima - Cribroelphidium hallandense* Biofacies (2) is characterized by highly variable proportions of *Buliminella elegantissima* (6-25%) and *Cribroelphidium hallandense* (0-28%). Both *Epistominella vitrea* (7-20%) and *Cribroelphidium excavatum* (6-21%) are relatively abundant throughout. *Stainforthia feylingi* (1-12%), *Nonionella stella* (2-8%) and *Islandiella norcrossi* (1-5%) are also common but not so abundant. The proportion of *Buccella frigida* (3-15%) increases stratigraphically upward. The proportion of *Cassidulina reniforme* also increases from only 1-2% in the stratigraphically lower part of the biofacies to 10-23% in the upper part. Biofacies 2 is characterized by the highest faunal diversities observed in the core; this is especially true in the lower part of the stratigraphic interval covered by the biofacies, where it occurs within the B_1 Lithofacies. The faunal transition from Biofacies (2) to Biofacies (3) is gradual as graphically indicated by the close euclidean distance between the two biofacies (Figs. 2, 4).

The *Islandiella helenae - Cassidulina reniforme* Biofacies (3) is composed of low diversity, low abundance assemblages. This biofacies is dominated by high proportions of *Islandiella helenae* (20-52%) and *Cribroelphidium excavatum* (8-31%). *Epistominella vitrea* (4-25%), *Buccella frigida* (3-13%) and *Islandiella norcrossi* (0-10%) are less abundant. *Cassidulina reniforme* varies in abundance (1-14%) but is generally more common here than in any other biofacies. Unfortunately, this interval has been subject to dissolution, as indicated by etched foraminiferal tests. *Cassidulina reniforme*, which is particularly susceptible to dissolution, may otherwise have been more abundant. Dissolution may also explain the low diversity, low abundance nature of Biofacies 3. This fauna is typical of relatively low salinity, glacial marine conditions.

The *Nonionellina labradorica* Biofacies (4) is characterized by high proportions of *Nonionellina labradorica* (14-37%). This species is characteristic of cool to cold, normal salinity waters. Moderate numbers of *Cribroelphidium foraminosum* (11-13%) also characterize this biofacies. Relict populations of *Islandiella helenae* (0-15%) and *Cassidulina reniforme* (2-15%) are common only in the lower part of

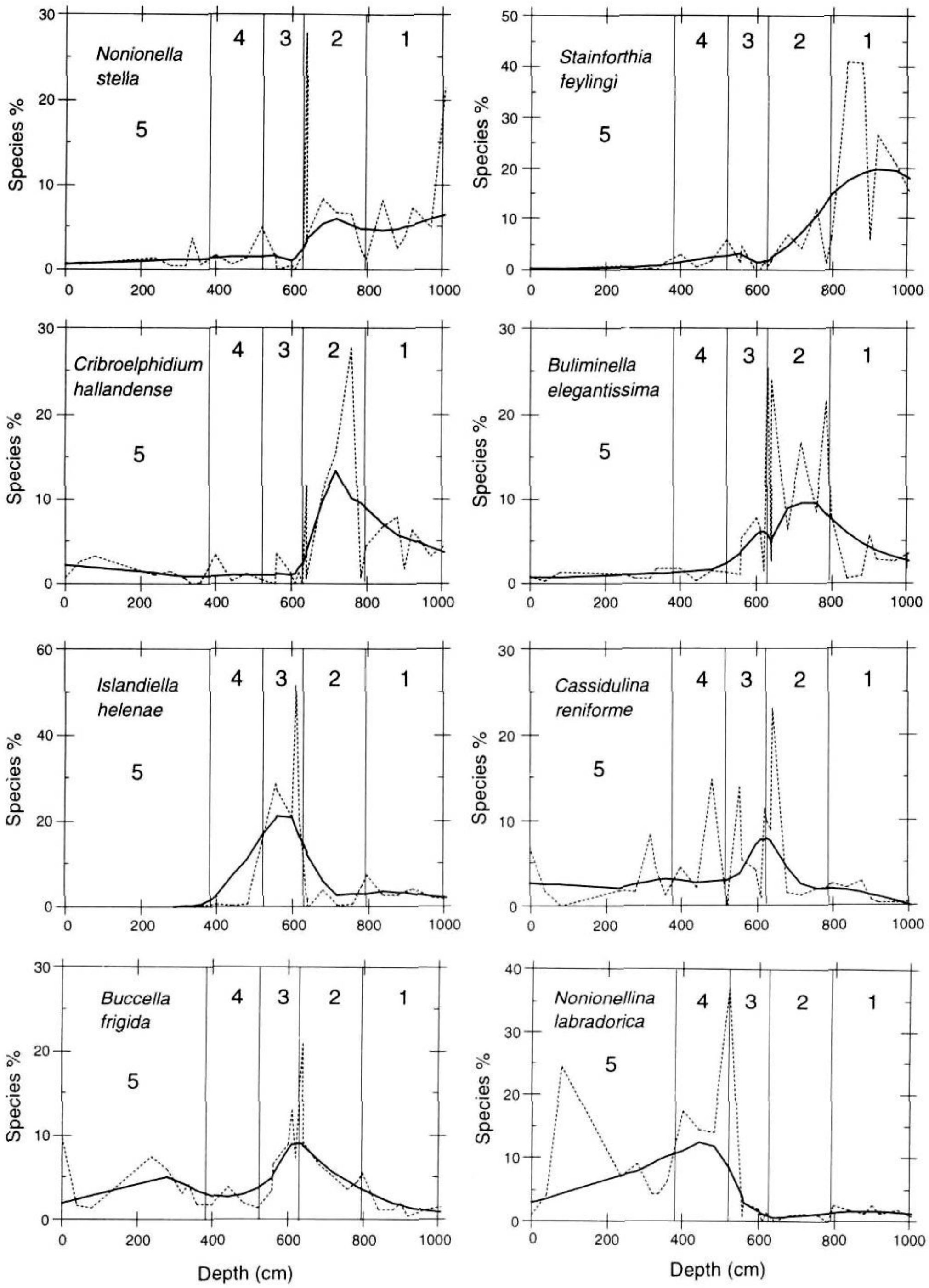


FIGURE 5. Weighted faunal distributional graphs generated for each of the main species encountered, as well as the number of species, number of temperate species, % temperate species, % planktics and Shannon diversity index. The dotted curves are recorded percent abundances while the bold, solid lines are computer generated weighted curves. Vertical lines mark biofacies limits.

Graphiques pondérés de distribution pour chacune des principales espèces rencontrées, de même que pour le nombre d'espèces, le nombre d'espèces tempérées, le % d'espèces tempérées, le % d'espèces planctoniques et l'indice de diversité de Shannon. Les courbes pointillées montrent les pourcentages observés tandis que les courbes épaisses représentent les valeurs pondérées. Les lignes verticales marquent les limites des biofaciès.

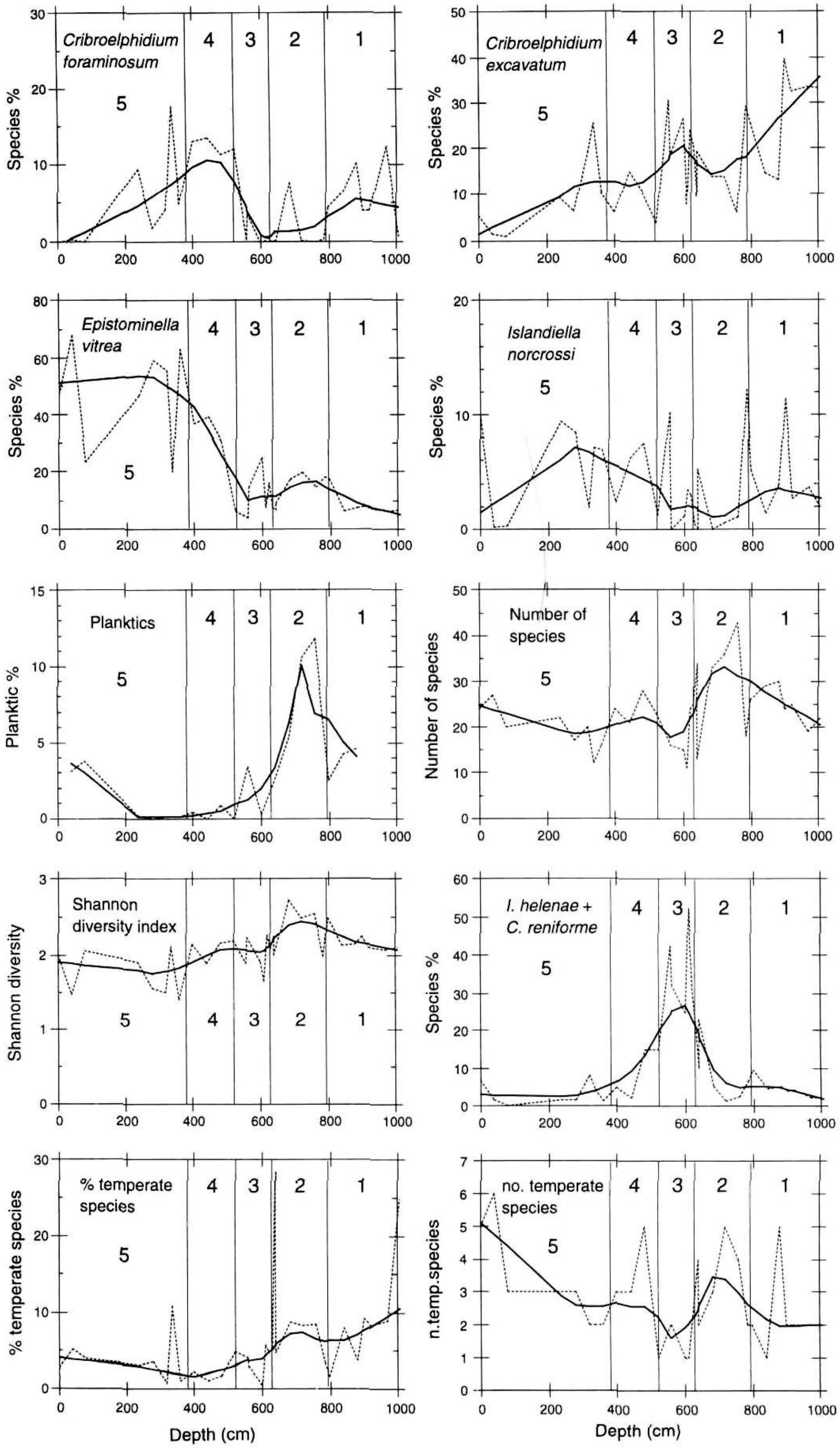

Cribroelphidium foraminosum
Species %
Cribroelphidium excavatum
Epistominella vitrea
Islandiella norcrossi
Planktics
Planktic %
Number of species
Shannon diversity index
Shannon diversity
I. helenae + C. reniforme
% temperate species
no. temperate species
n.temp.species
5
4
3
2
1
0
200
400
600
800
1000
Depth (cm)

TABLE I

Radiocarbon dates on shell material extracted from cores END 84B-08 and 10, originally published by Luternauer et al. *(1989b)*

Core	Depth in Core (cm)	Lithologic Unit	Radiocarbon Date (yr BP)	Corrected Radiocarbon Date (yr BP)	Laboratory Number	Dated Material
END 84B-10	50-52	C	9720±70	8990	TO-169	*Yoldia* sp.
END 84B-10	563-565	B_3	10,800±80	10,070	TO-170	*Macoma* sp.
END 84B-10	773-775	B_1	12,200±80	11,470	TO-171	Gastropod
END 84B-08	509-511	B_2	11,990±90	11,260	TO-79	*Macoma* sp.

The corrected values are from Mathewes *et al.* (1993). Radiocarbon date corrections based on Southon *et al.* (1990).

Biofacies 4. These two species are almost absent stratigraphically above this interval of the core. *Epistominella vitrea* increases stratigraphically upward from 6 to 39%.

The *Epistominella vitrea* Biofacies (5) is overwhelmingly dominated by the nominative species (20-78%). *Cribroelphidium foraminosum* (up to 18%) and *Cribroelphidium excavatum* (up to 25%) are also important in the stratigraphically lower part of this biofacies. The proportion of uvigerinids becomes markedly higher in the uppermost samples.

The sample obtained at the 638 cm level of the core was collected within a 13 cm mud bed containing large numbers of shell fragments. This unique foraminiferal population formed an anomalous single sample cluster and is probably the result of specimens having been reworked from neighbouring areas or from underlying late Glacial units. The foraminiferal assemblage is characterized by high proportions of large, fully developed specimens of *Nonionella stella* and *Buccella frigida* and is situated within the B_2 Lithofacies of the core, deposited during a low sea-level stand (Luternauer *et al.*, 1989b).

Cribroelphidium excavatum phenotype "*clavata*" (all our material belongs to the "*clavata*" phenotype) displays an overall decline in abundance up core. A similar decline in the abundance of this glacial indicator species through the late Quaternary and early Holocene, as conditions change from glacial to non-glacial, has been reported by many researchers (Feyling-Hanssen, 1964; Vilks, 1980, 1981). In contrast, *Epistominella vitrea* shows an overall increase in abundance up core, dominating the fauna in the upper part. This species characterizes many modern shelf environments from Oregon to Alaska (Bergen and O'Neil, 1979; Echols and Armentrout, 1980; Snyder *et al.*, 1990).

Weighted distribution graphs of the Shannon diversity and total number of species (Fig. 5) shows that diversities are highest in Biofacies 2 and lowest in Biofacies 3. These trends are in part the result of the high number of unilocular foraminiferal species found in Biofacies 2 and the poor preservation of the foraminiferal fauna in Biofacies 3. The proportion of temperate species (defined below) in relation to the total number of specimens is greatest below the Biofacies 3 level of the core, harmonizing well with the diversity results.

COMPARISON TO NEARBY CORE END 84B-08

Of the cores studied by Patterson (1993), core END 84B-08 is the one geographically nearest (6 km away) to 84B-10 and best sampled (Fig. 6). As in core END 84B-10 *Cribroelphidium excavatum* decreases in abundance upcore while *Epistominella vitrea* increases. *Cassidulina reniforme* peaks in the upper part of Lithofacies B_2 in both cores (and at isochronous levels in the other cores examined by Patterson, 1993). In addition, *Cribroelphidium foraminosum*, *Nonionellina labradorica*, and *Stainforthia feylingi* (reported as *Stainforthia* sp. in Patterson, 1993) also show similar distributional trends in both cores. Unfortunately, *Islandiella norcrossi* and *Islandiella helenae* were lumped in the Patterson (1993) study so direct comparison of the distribution of these species is not possible. In summary, these data from core END 84B-08 constitute collateral evidence to support the zonation reported here as representative of the foraminiferal succession in Goose Island Trough and probably throughout Queen Charlotte Sound during the late Quaternary.

DISCUSSION

RECOGNITION OF ARCTIC AND TEMPERATE FORAMINIFER INDICATOR SPECIES

The identification of species limited exclusively to temperate or Arctic-like conditions is critical if paleoceanographic fluctuations such as Younger Dryas-like cooling are to be recognized. Using distributional information compiled in 18 references detailing foraminiferal distribution in high latitude areas (Appendix 3), we have differentiated temperate and Arctic shelf species (Appendix 2). Exclusively temperate species are defined to include species reported from the northeastern Pacific Ocean south of the Aleutian Islands but not from either the Bering Sea or the Arctic Ocean. Exclusively Arctic species are defined to include those species reported only from north of the Aleutian Islands. We did not set our boundary at the Bering Strait as we prefer a more restrictive concept of temperate species to emphasize the fact that temperature-sensitive species are present in our core through most of the time interval under study. *Bolivina minuta* was excluded from our list because it lives

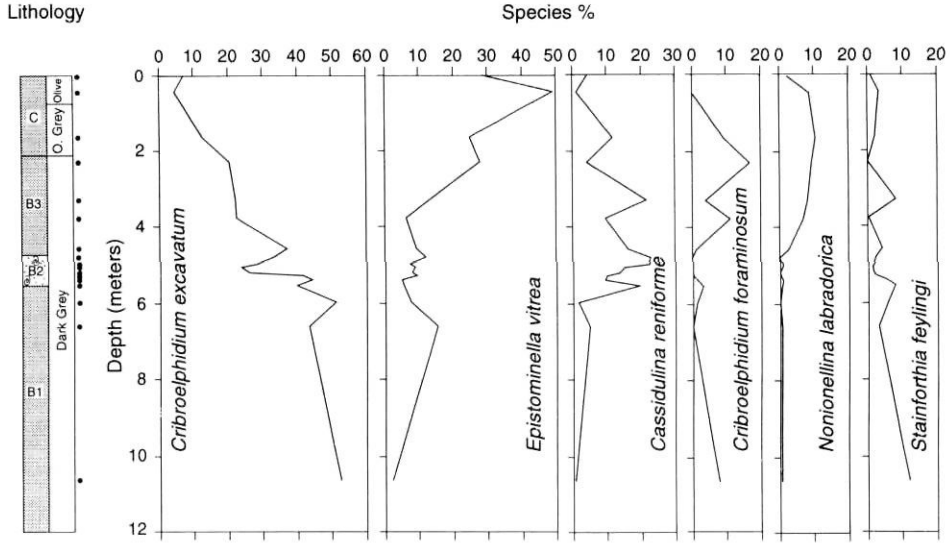


FIGURE 6. Stratigraphic section of core END 84B-08 showing lithology and distribution of key indicator species. Dots beside stratigraphic column indicate sampled horizons (modified after Patterson, 1993).

Coupe stratigraphique de la carotte END 84B-08 montrant la lithologie et la distribution des principales espèces indicatrices. Les points à côté de la colonne stratigraphique indiquent les niveaux échantillonnés (modifié d'après Patterson, 1993).

only in deep water; extremely rare forms (*e.g.*, most unilocular foraminifera) were also excluded.

Our literature search shows that very few exclusively temperate or Arctic foraminiferal species are found along the Pacific margin. Most of the foraminiferal species recovered from core END 84B-10 are thus cosmopolitan. When considering species identified from core END 84B-10, only *Islandiella helenae* and *Cassidulina reniforme* are limited to, or prefer, Arctic-like temperatures (Guilbault, 1980, 1989, for *I. helenae*; Sejrup and Guilbault, 1980, Elverhøi *et al.*, 1980, and Schafer and Cole, 1986, for *C. reniforme*). The presence of these species is critical to the recognition of cold depositional intervals within the core.

Twelve species qualified as exclusively temperate by our definition (*e.g.*, *Nonionella stella* and *Epistominella pacifica*) but collectively represented less than 10% of the fauna in all but four samples (Fig. 5). Of these four samples, the fauna found at 638 cm was probably reworked and the total specimen count at 53 cm was too low to provide statistically reliable results. In general, the proportion of exclusively temperate fauna remains relatively low and constant through the core with marginally higher values in Biofacies 1, 2 and the upper part of Biofacies 5. Since only two species, *Nonionella stella* and *Epistominella pacifica* constitute the major portion of the sum of temperate species counts, these results must be interpreted with caution (Fig. 5). The inordinate influence of these species on the curve indicates that this diagram cannot be interpreted beyond noting that some temperate foraminifera are found throughout the core. The curve showing the "number of temperate species" present, regardless of their percentage, may better illustrate the distribution of these species (Fig. 5). The most notable feature of the three temperature-related graphs (also including *Islandiella helenae* and *Cassidulina reniforme*) is the decrease in warm-water indicators and the increase in cold-water indicators at the boundary between Biofacies 2 and 3.

It may be argued that a large proportion of the recovered temperate indicators are reworked from pre-Wisconsinan strata (by opposition to sample 638 which represents penecontemporaneous redeposition). However, as most temperate species now inhabiting the shelf off the west coast of North America are absent from these sediments, in particular such extremely abundant and robust species as *Islandiella tortuosa* and *Islandiella californica*, we find little support for this hypothesis.

Glacial marine late Pleistocene deposits in and off eastern Canada rarely contain any temperate species (*e.g.*, Guilbault, 1993; Rodrigues *et al.*, 1993; Scott *et al.*, 1984, 1989; Vilks, 1980, 1981; Vilks and Mudie, 1983; Vilks and Rashid, 1976). Two factors may explain the presence of a background level of exclusively temperate species even during cold water intervals: (1) any glacial advance between 12,000 and 9000 years BP was within the fjords, quite far away from the core depositional site (Luternauer *et al.*, 1989b); and (2) hydrographic conditions relating to the California Undercurrent may have brought warmer water through deep troughs up to the core site (see Paleoceanography subsection of Discussion), resulting in the presence of significant proportions of species such as *Nonionella stella* and *Epistominella pacifica*. The California Undercurrent flows northward along the North American coast at depths below 250-300 m; it has been reported as far north as the northern tip of Vancouver Island (Hickey, 1979; Mackas *et al.*, 1987) and it is likely to extend still further north during periods of prolonged upwelling. Upwelling along the coast causes some of this slightly warmer water to advect onto shelf areas, especially into submarine canyons such as Goose Island Trough.

INTERPRETATION OF FORAMINIFERAL BIOFACIES

The five biofacies identified can be related to distinct sets of environmental conditions such as water depth, temperature and salinity. For these reasons we will discuss the depositional scenarios for each biofacies separately, beginning at the base of the core.

Cribroelphidium excavatum - Stainforthia feylingi Biofacies (1)

The *Cribroelphidium excavatum - Stainforthia feylingi* Biofacies (1) found between the base of the core and 784 cm was deposited in a deep shelf environment (>100 m) under normal salinity conditions. This depth estimate is based on the overall faunal composition and more particularly on the proportions of *Nonionella stella* which are higher than in Biofacies 3 to 5 further up the core. In the Gulf of Alaska, this species is also more common in deeper shelf habitats than in shallow-turbulent water (Echols and Armentrout, 1980). The high proportions of *Cribroelphidium excavatum* are interpreted to represent relict populations more characteristic of the earlier full glacial conditions (A Lithofacies, not sampled here). The high proportion of *Stainforthia feylingi* is difficult to interpret. Species of *Stainforthia* generally inhabit deeper waters. However, according to Scott *et al.* (1984), a high percentage of *S. feylingi* (reported as *Fursenkoina fusiformis*) could be an indication of low dissolved oxygen content. This interpretation is mostly based on modern results from the deep Baie des Chaleurs (Schafer and Cole, 1978) and we would prefer to have more data before applying it to Queen Charlotte Sound. The ease with which this species can be reworked makes it difficult to use for paleoenvironmental reconstruction.

Sedimentologically, this interval consists of finely laminated to massive dark gray muds with minor shells (B_1 Lithofacies of Luternauer *et al.*, 1989b). Deposition occurred between 12,200 and 11,470 years BP (Table I; Luternauer *et al.*, 1989b). The age estimate for the base of the core derives from the absence of ice rafted debris typical of the A Lithofacies whose termination was dated by Luternauer *et al.* (1989b) at no later than 12.2 ka BP (corrected age provided by Patterson, 1993). Cool oceanographic conditions existed during deposition of the unit.

Buliminella elegantissima - Cribroelphidium hallandense Biofacies (2)

The *Buliminella elegantissima - Cribroelphidium hallandense* Biofacies (2) found between 784 and 630 cm was deposited between about 11,470 and 11,260 years BP and encompasses the upper part of the B_1 Lithofacies as well as sandy muds of the lower part of the maximum lowstand of the B_2 Lithofacies (Luternauer *et al.*, 1989b). The age for the end of the interval is based on correlation with a ^{14}C date from the B_2 Lithofacies of nearby core END 84B-08 (Fig. 6; Table I). As this core was taken at a similar water depth (173 m) only 6 km from core END 84B-10, the age of the B_2 Lithofacies may be assumed to be approximately the same at both sites.

Sedimentological evidence (Luternauer *et al.*, 1989b) indicates that, despite a global eustatic sea-level rise during this interval, relative sea level was steadily falling at this site as the glacial forebulge generated by glacial retreat passed over the area. Clague (1983) provided evidence that there had been strong glacio-isostatic sea-level changes on the British Columbia shelf associated with retreat of the Cordilleran Ice Sheet. Our best paleo-depth estimate for site END 84B-10 during maximum lowstand is 75-90 m. This calculation is based on the results of two recent sea-level studies in the area. Josenhans *et al.* (1993a, 1993b) have identified lacustrine deposits on the shelf off southern Queen Charlotte Island ponded behind a sill at a depth of 110 m. Luternauer *et al.* (1989a) identified *in situ* tree roots dated between 10,500 and 10,000 years BP on Cook Bank presently at a water depth of 95 m. This change in sea level is significant because once water depth fell below 100 m, the END 84B-10 core site would have come under the influence of surface waters. Detailed examination of the seasonal water property structure in the region has shown that the maximum mixing depth, up to the top of the permanent halocline/pycnocline, is 100 m (Dodimead, 1980).

The increase of *Buliminella elegantissima* in Biofacies 2 may indicate a greater influx of land-derived organic matter, as suggested by the results of Harmon (1972) off the mouth of the Columbia River. A large volume of organic matter would have been readily available from the numerous recently emergent nearby islands surrounding the core site on all sides. Vegetational cover had been gradually developing since deglaciation (Mathewes, 1993) as the islands were increasing in size in response to the lowering sea level (Fig. 3).

The high percentage of *Cribroelphidium hallandense* could be interpreted as an indication of depressed salinity. However, according to unpublished data by Patterson and Guilbault, late Pleistocene and Holocene deposits on the British Columbia shelf contain large numbers of exceptionally small phenotypes of *Cribroelphidium hallandense*. In many cases, these specimens are found in assemblages that are obviously representative of deep shelf normal salinity conditions. As these same small phenotypes are observed in core 84B-10 we therefore think that the presence of *Cribroelphidium hallandense* provides inconclusive evidence of salinity variation.

Despite reduced water depth, salinities remained at or near normal marine levels (~34‰) during deposition of the part of Biofacies 2 that occurs within the B_1 Lithofacies. The very high foraminiferal diversity found in samples 759 cm to 681 cm (Shannon diversity index of over 2.5) along with the highest proportion of planktic foraminifera in the core (11.8%) are indicative of open shelf conditions.

Islandiella helenae - Cassidulina reniforme Biofacies (3)

The *Islandiella helenae - Cassidulina reniforme* Biofacies (3; 630-556 cm) spans the top of the B_2 Lithofacies (maximum lowstand of 75 to 90 m) and the base of the B_3 Lithofacies. The age of the base of this biofacies is not well constrained in this core. However, the base of the *Cassidulina reniforme* abundance spike was well dated in several cores in the Patterson (1993) study. As Patterson (1993) determined that this spike was isochronous in all cores, a ^{14}C date of around 11,100 years BP, obtained from core END-84B-04 in Moresby Trough, is extrapolated to this core (Patterson, 1993; Mathewes *et al.*, 1993). Since Biofacies (3) was deposited between about 11,100 and 10,000 years BP, it is isochronous with the Younger Dryas cooling event of the North Atlantic region. The dramatic shift in paleoceanographic conditions during deposition of this unit corroborates previous terrestrial and marine evidence of a Younger Dryas-like isochronous cooling along the British Columbia coast (Patterson, 1993; Mathewes *et al.*, 1993; Mathewes, 1993). The decline of planktic foraminifera to 2.6% in the uppermost B_2 Lithofacies sample (628 cm) approximately coincides with maximum lowstand indicating more restrictive conditions, as discussed below. A sharp reduction in benthic foraminiferal diversity also takes place at the same level.

The overall assemblage of foraminifera in Biofacies 3, especially the high percentages of *Islandiella helenae* and *Cassidulina reniforme* (see Fig. 5, separate and cumulative occurrence plots for both species), both Arctic in preference, indicate very cold water. The abundance of *Cassidulina reniforme* is typical of the glacial conditions found in ice-proximal Kongsfjorden Fjord, Spitsbergen (Elverhøi, 1980).

The secondary peak of *Cribroelphidium excavatum* in this biofacies (Fig. 5) is also suggestive of a return to more Arctic conditions. Hald and Vorren (1987) and Osterman (1984) interpret peak occurrences of this taxon during deglaciation as an indication of the temporary return to a cold, glaciomarine setting. Further evidence of cold water is provided by the low (1.6-2.2) Shannon diversity index, a level considered normal in glacial seas but too low for temperate open shelves (Lagoe, 1980). The minimal presence of the temperate species *Epistominella pacifica* and *Nonionella stella* in these samples indicates that moderating marine influences, though present, were minor. Our results correspond well with sedimentological evidence indicating that glacial readvances during this phase did not extend out of the coastal fjords (Luternauer *et al.*, 1989b). These results also indicate that present-day foraminiferal faunas reported from glacial fronts in southern Alaska (Echols and Armentrout, 1980) are not good analogs of Biofacies 3. These Alaskan foraminiferal faunas, at least those living in the deeper parts of the fjords, contain a much higher proportion of temperate species. This is because the Alaska glaciers occur in areas of temperate climate and calve into waters influenced by relatively warm offshore currents (4° to 6°C at 100 m).

The dominance of *Islandiella helenae* in Biofacies 3, common in lower salinity regimes such as the Champlain Sea and modern glacial seas (Guilbault, 1989, 1993), indicates that salinities were lower than during deep open shelf deposition of Biofacies 2. The modern analogs quoted by Guilbault (1980, 1989, 1993) suggest a range of 25 to 32‰ for *C. reniforme - E. excavatum - I. helenae* assemblages. For the late Glacial Queen Charlotte Sound setting, which, even at its shallowest, was more open than the Champlain Sea, salinities of less than 30‰ appear improbable and therefore a paleosalinity of 30-32‰ shall be assumed for Biofacies 3. The fact that *Islandiella helenae* cannot survive in waters with salinity values lower than approximately 25‰ provides a lower salinity constraint and suggests that at maximum lowstand the site was well beneath the summer pycnocline (presently ≈ 40 m in Queen Charlotte Sound; Dodimead, 1980). A straightforward interpretation of the *Islandiella helenae - Cassidulina reniforme* Biofacies would conclude that a decrease in bathymetry brought on by passage of the glacial forebulge blocked the site from the more saline and warm waters that supported the *Buliminella elegantissima - Cribroelphidium hallandense* Biofacies. However, the presence of a low salinity surface plume from glaciers calving at the head of fjords some distance away on the mainland could not alone explain how salinities declined to well below normal marine levels at 75 to 90 m water depth (at maximum low stand) and remained low for some time afterwards even when water depth was once again increasing. An understanding of existing climatic and paleoceanographic conditions in the area is the key to solving this problem and is discussed in the Paleoceanography section below.

Nonionellina labradorica Biofacies (4).

The *Nonionellina labradorica* Biofacies (4) is contained entirely within the B_3 Lithofacies. According to sedimentological data, a major transgression rapidly re-submerged much of the emergent shelf to present day sea levels (Luternauer *et al.*, 1989b). The presence of only a minor component of *Buliminella elegantissima* through the balance of the core corroborates these results. Deposition of Biofacies 4 is extrapolated to have occurred between ~10,000-9700 years BP.

The replacement of the *Islandiella helenae* and *Cassidulina reniforme* - dominated Biofacies 3 by the *Nonionellina labradorica* - rich Biofacies 4 is interpreted to indicate normal salinity conditions. For example, in the modern Gulf of St. Lawrence, Rodrigues and Hooper (1982) reported *Nonionellina labradorica* as dominant only in deep waters where salinity is 34‰ or more. In normal salinity glacial marine deposits off the Labrador Shelf, Vilks (1980) also reported abundant *Nonionellina labradorica.* In addition, on a recently deglaciated sea bottom in Spitsbergen, where salinity was also at near normal marine values (33-34‰), Elverhøi *et al.* (1980) found *Nonionellina labradorica* to be common among the early colonizers, whereas *Islandiella helenae* appeared only sporadically. Conversely, Rodrigues and Hooper (1982) reported *Islandiella helenae* to only dominate in shallower waters characterized by salinities of less than 33-34‰. Similarly, in sediments of the inland and brackish Champlain Sea, Guilbault (1993) found abundant *Islandiella helenae* while *Nonionellina labradorica* was rare and restricted to the easternmost part of the basin. Our literature search for temperate species has shown *Nonionellina labradorica* to be widely distributed in the Arctic. Thus, temperature is probably not the limiting factor for this species.

Although the cold-water species *Cassidulina reniforme* and *Islandiella helenae* are still important in Biofacies 4, they are diminishing (*e.g.*, *Islandiella helenae* will disappear at the base of Biofacies 5). This trend suggests that the presence of cold-water species are largely relict in Biofacies 4 and 5. The overall faunal composition also indicates that lower salinity conditions had terminated.

Epistominella vitrea Biofacies (5)

The balance of the core is characterized by the *Epistominella vitrea* Biofacies (5). Biofacies 5 (spanning the B_3 and C lithofacies) was deposited from ~9700-8900 years BP. The faunal makeup is similar to modern-day temperate waters reported from off the coast of southern Alaska (Echols and Armentrout, 1980). However, samples from the Alaskan shelf and fjords are not so overwhelmingly dominated by *Epistominella vitrea* as they are here. The high frequency of this species has the effect of producing exceptionally low faunal diversities (Shannon diversities of 1.5-2.1) for an open marine, outer shelf environment. The dominance of a single species under supposedly more favorable, post-glacial temperate conditions suggests that some unknown environmental stress may have been a factor favoring one species at the expense of others.

PALEOCEANOGRAPHY

Depending on the season, wind patterns along the Pacific coast are controlled by the location and intensities of two major, semi-permanent atmospheric pressure cells: the Aleutian Low (AL) and the North Pacific High (NPH; Kendrew and Kerr, 1955; Thomson, 1981). In the northeast Pacific there is a seasonal oscillation between the two systems as a result of solar radiation. During the summer, when the land is hot and the ocean cool, the region comes under the influence of the NPH, a large-scale clockwise rotating wind pattern that moves up from the south (Fig. 7). The combination of Coriolis effect and the typically northward and eastward blowing NPH winds generates a southward coastal drift and an offshore Ekman transport. This transport causes surface water to be advected offshore and triggers the upwelling, along the continental margin, of relatively warm high salinity water of the California Undercurrent which flows northward below a depth of 250-300 m in the summer. This wind induced upwelling is slow, 1-10 m/day, but has a profound effect over thousands of square kilometers of the west coast of North America (Thomson, 1981; Fig. 8A).

During the winter, as atmospheric pressure increases over the cold land and decreases over the relatively warm ocean, the NPH is pushed southward and the area comes under the influence of the AL, a counterclockwise rotating weather pattern that centers in the western Gulf of Alaska (Fig. 7). In this case, the combined Coriolis effect and south blowing winds generate a northward coastal drift and a consequent onshore Ekman transport. The piling up of lower density surface water near shore ("downwelling") maintains cold, low salinity conditions over the shallower parts of the shelf and prevents upwelling. In winter, the California Undercurrent is confined to the persistent upwelling regions of California and deep currents along the coast of British Columbia become variable (Thomson, 1981; Fig. 8B).

At the time of deposition of Biofacies 1 and lower Biofacies 2 (B_1 Lithofacies), conditions would be approximately like at present, except that the Aleutian Low would be intensified and the upper ocean bifurcation zone between the Alaska and California Currents would be shifted to the south (Thomson, 1981). In addition, the coastal transition zone separating the predominantly downwelling domain in the north from the predominantly upwelling domain in the south would lie to the south of the northern tip of Vancouver Island. In summer, offshore Ekman transport and associated upwelling would be reduced, and the deep poleward transport of southern warm and saline water by the California Undercurrent would be less than today. The troughs would still act as conduits for enhanced advection

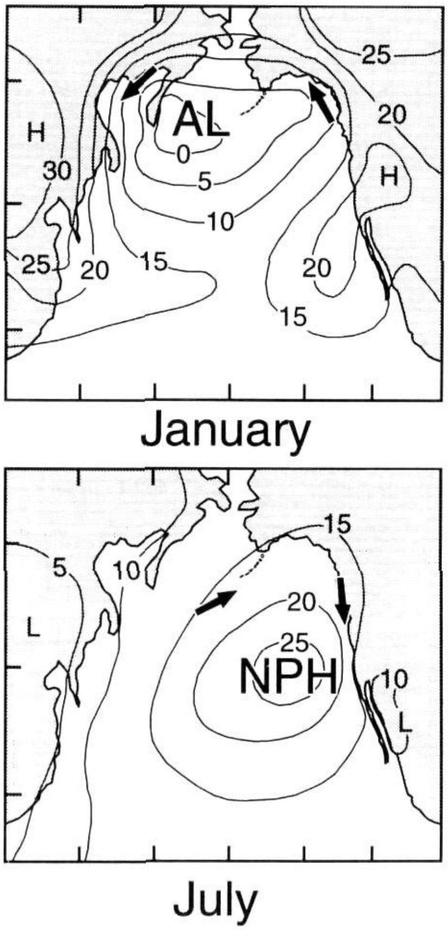


FIGURE 7. Air pressure at sea level in January and July for the northeast Pacific region from 1951-1970. In winter, when the land is cold and the ocean relatively warm, a large-scale counterclockwise low pressure gyre (Aleutian Low [AL]) develops, dominating the weather over the entire northeastern Pacific. In summer, when the land is hot and the ocean relatively cool, a large-scale clockwise high pressure cell (North Pacific High [NPH]) moves up from the south and dissipates the AL. Arrows indicate prevailing wind direction. Value on diagram + 10,000 divided by 10 gives pressure in millibars (modified after Favorite, *et al.*, 1976).

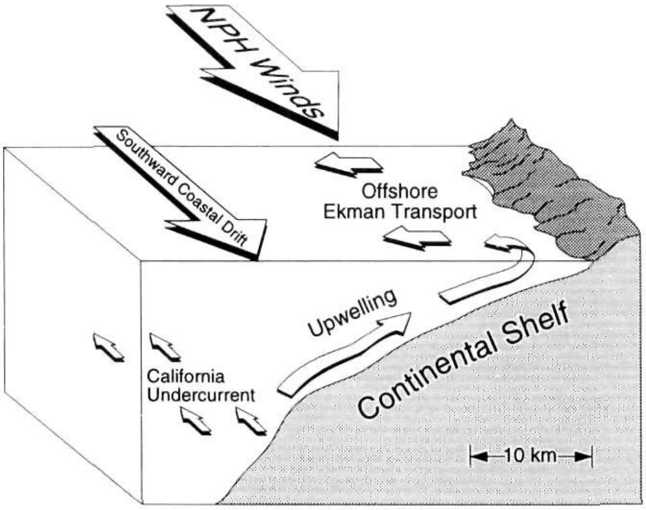
Pression atmosphérique au niveau de la mer en janvier et en juillet dans la région nord-est du Pacifique entre 1951 et 1970. En hiver, quand le continent est froid et l'océan relativement chaud, une grande dépression cyclonique (dépression des Aléoutiennes [AL], antihoraire) se développe, commandant le temps sur tout le nord-est du Pacifique. En été, quand le continent est chaud et l'océan frais, un grand anticyclone (Anticyclone du Pacifique Nord [NPH], horaire) monte du sud et dissipe l'AL. Les flèches montrent les vents dominants. La pression en millibars est donnée par la valeur du graphique + 10 000 divisée par 10 (modifié de Favorite et al., 1976).

of oceanic water into the shelf environment while top-to-bottom mixing, causing low salinities and temperatures, would be confined to the shallow inner portions of the continental shelf, much like today. Temperate and stenohaline foraminifera would still have relatively easy access to the paleo-water depth of 75-90 m found at core site END 84B-10 through main troughs, hence the high diversities.

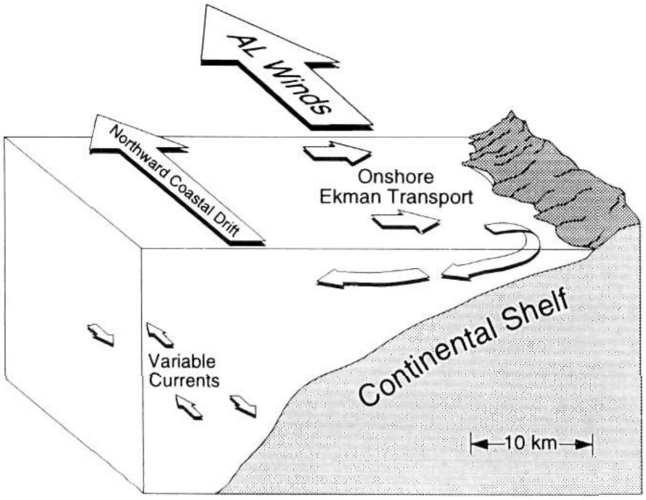
During the eastward progression of the forebulge and resultant oceanic shallowing in the region (B_2 Lithofacies, upper Biofacies 2), upwelling offshore water would be much less able to penetrate onto the shallow shelf. California Undercurrent water could only reach core site END 84B-10 during periods of strong estuarine outflow and strong north blowing winds. On the average, the number of planktic foraminifera would decline, as well as the percentage and number of temperate and/or stenohaline species. This is the situation we observe in the upper part of Biofacies 2. At that time, the northern end of Hecate Strait would have become closed (modern bathymetry < 100 m) so that Queen Charlotte Sound and Hecate Strait would have become a coastal basin (Barrie *et al.*, 1993; Fig. 1). We tentatively name that enclosed basin the "Hecate Sea". Brackish water would have accumulated in this basin but as long as wind conditions remained more or less unchanged, upwelling water would have still penetrated far enough onshore to be a factor.

We propose that the observed boundary between Biofacies 2 and 3 coincides with, and is the result of, a westward shift in the AL accompanied by cooling over the northwest coast of North America (cooling of the land). This shift led to greater storm activity and increased precipitation (the latter is indicated by both Mathewes, 1993, and Ebbesmeyer *et al.*, 1989). The combination of increased southerly winds, shorter summers and longer winters, resulted in an increased volume of cold, brackish water flowing into the Hecate Sea. Wind and tidal mixing of this high volume runoff eventually produced a strong oceanic density front separating the cold, low salinity well-mixed water mass filling the Hecate Sea from the warm, salty oceanic water offshore. There was negligible penetration of water from the ocean, either deep or shallow. This setting favored the development of glacial low-diversity assemblages dominated by *Islandiella helenae, Cassidulina reniforme* and *Cribroelphidium excavatum*. The proportion of planktic as well as temperate/stenohaline foraminiferal species, as observed, would also have been minimal under this scenario.

The end of the cold Younger Dryas-like phase was accompanied by a shift of the AL back to a more normal



A. North Pacific High influenced coastal circulation in Queen Charlotte Sound.



B. Aleutian Low influenced coastal circulation in Queen Charlotte Sound.

FIGURE 8. A. Main features of upwelling-favorable wind conditions in Queen Charlotte Sound during the summer. Northerly North Pacific High (NPH) winds generate a southward surface flow and a consequent offshore Ekman transport inducing upwelling, thus bringing high salinity deep waters closer to the surface. The relatively warm California Undercurrent flows north below 250-300 m depth. Upwelled water moves up through the main troughs (such as Goose Island Trough). B. Main features of wind-induced downwelling in Queen Charlotte Sound during the winter. Southerly Aleutian Low (AL) winds generate a northward drift and a consequent onshore Ekman transport. This causes an accumulation of low density less saline water on the shallower parts of the shelf, thus restricting the upwelling of deep water (modified after Thomson, 1981).

A. Caractéristiques principales d'un régime de vent favorable à la remontée des eaux profondes (upwelling) dans le bassin de la Reine-Charlotte pendant l'été. Les vents de l'anticyclone du Pacifique Nord (NPH), soufflant du nord, entraînent une dérive de surface vers le sud et conséquemment un transport d'Ekman vers le large, ce qui provoque une remontée vers la surface des eaux salées profondes. Le sous-courant de Californie, relativement chaud, coule vers le nord à une profondeur supérieure à 250-300 m. La remontée s'effectue à travers les principales cuvettes (comme celle de Goose Island) B. Caractéristiques principales d'un régime de vent favorable au downwelling dans le bassin de la Reine-Charlotte durant l'hiver. Les vents de la dépression des Aléoutiennes (AL), soufflant du sud, engendrent une dérive vers le nord et en conséquence un transport d'Ekman vers la côte. Ceci entraîne une accumulation d'eaux hyposalines moins denses dans les parties peu profondes de la plate-forme, bloquant ainsi la remontée des eaux profondes (modifié d'après Thomson, 1981).

position, a marine warming trend, fewer storms and reduced runoff. This led to the return of normal conditions along the coast. In addition, with the unrelated rapid increase in water depth, as indicated by the faunas of Biofacies 4 and 5 (B_3 and C lithofacies) the Hecate Sea ceased to exist and Hecate Strait and Queen Charlotte Sound reverted to their present state. Unfortunately, it is difficult to precisely pinpoint the return to normal winter/summer weather patterns and the termination of the west coast Younger Dryas-like cooling event. This is because the rapid rise in sea level after 10,000 years BP quickly brought the core site to more than 100 m water depth within easy reach of upwelling water whose flow patterns were independent of climate conditions.

A very important point that must be understood is that environmental conditions corresponding to the beginning of Biofacies 3 deposition were *not* the result of a regression bringing the core site within cold brackish surface water. Deposition of Biofacies 3 began only during deposition of the upper part of the shallow B_2 Lithofacies and went on during deposition of the B_3 Lithofacies when water depth was rapidly increasing. Thus, Biofacies 3 is the result of a change in circulation brought about by a shift toward colder climate.

It has been suggested to us that oceanographic effects similar to those proposed by our model could be generated by the massive drainage of several large lakes that existed in the interior of the Yukon and British Columbia at about the same time as the Younger Dryas (Mathews, 1944; Eyles, 1987; Eyles and Clague, 1991; Roberts, 1991; Jackson *et al.*, 1991; Ryder and Maynard, 1991). Drainage of these cold lakes would send plumes of cold low salinity water into the Hecate Sea. However, in Champlain Sea sediments in eastern Canada, even the massive drainage of Lake Agassiz had little more effect than to slightly thicken the seasonal superficial brackish water layer and make it less saline than before (Guilbault, 1993). Deeper waters of the Champlain Sea remained as saline as before and foraminifer populations remained unchanged. Furthermore, on the Scotian Shelf, where the impact of glacial meltwater floods was probably comparable to that on Queen Charlotte Sound, Scott *et al.* (1989) found no evidence for such floods in the foraminiferal assemblages. Similarly, benthic foraminiferal faunas of the Hecate Sea would have been unaffected by the passage of low salinity plumes in the surface pycnocline. In addition, the effects of draining these lakes would have been short lived, terminating in a matter of days or weeks. For the reasons outlined above and because the cold phenomena that we have identified persisted for 1000 years, we reject this hypothesis.

SUMMARY

1. Normal marine conditions prevailed at the head of Goose Island Trough from ~12,200 to sometime between 11,470 and 11,260 years BP, although relict populations of *Cribroelphidium excavatum,* more indicative of full glacial conditions, still dominated the fauna. Even though sedimentological data points to a gradual reduction in depth, the high Shannon diversity index and the high proportion of *Nonionella stella* and *Epistominella pacifica* indicate near normal salinities (34‰) and warmer (than Arctic norms) water temperatures.

2. Through a combination of isostatic (the glacial forebulge arriving at the site) and eustatic factors, starting between 11,470 and 11,260 years BP, water depth reached a minimum of 75-90 m, as indicated by sedimentological data. Decrease in the Shannon diversity index and in the number of planktic foraminifera implies some restriction on the circulation of marine water but not a complete cutoff of upwelling. Salinities probably also decreased slightly.

3. From 11,260 to ~10,000 years BP, there was a significant decrease in water temperature and salinity unrelated to lowstand conditions. The co-dominance of *Cassidulina reniforme* and *Islandiella helenae* is indicative of both cold water conditions and reduced salinities (30‰). However, the presence of some temperate species indicates that conditions were not ice proximal. We propose that as part of the hemispheric climate changes accompanying development of Younger Dryas-like cooling, the AL pressure cell came to dominate western North America and the adjacent North Pacific nearly year round. This modification of present-day weather patterns resulted in persistent downwelling-favorable wind conditions and an accumulation of cold, brackish water on the shallower (< 100 m) parts of the continental shelf. These conditions had the effect of almost completely blocking the upwelling of warmer, saltier water. We tentatively name this restricted paleo-coastal basin, comprised of the modern Hecate Strait and Queen Charlotte Sound, the Hecate Sea.

4. Salinity and water temperatures returned to normal very quickly at core site END 84B-10 by ~10,000 years BP in conjunction with: (1) a rapid increase in water depth as the effects of the forebulge passage decreased; and (2) the unrelated termination of Younger Dryas-like cold weather patterns as the AL pressure cell became less dominant in the area. This rapid return to normal paleoceanographic circulation patterns is indicated by the almost complete replacement of *Islandiella helenae* by *Nonionellina labradorica*. By 9700 years BP a fauna dominated by *Epistominella vitrea*, similar to present-day faunas on the shelf, had developed indicating that essentially modern oceanographic conditions prevailed.

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APPENDIX 1

Statistically significant foraminiferal occurrences in samples containing statistically significant foraminiferal counts from core END 84B-10

ı core		0	40	78	237	279	319	335	359	399	441	481	521	556	561	598	610	620	628	638	641	681	718	759	784	799	839	879	900	920	970	1007
		0.063	0.125	1.000	0.250	0.250	0.234	0.189	0.250	0.500	0.500	0.250	1.000	0.189	1.000	1.000	1.000	0.125	0.125	0.125	0.125	0.250	0.250	0.500	0.250	0.250	0.125	0.125	0.125	0.125	0.125	0.125
ıunt		293	639	306	521	510	770	294	783	495	466	788	224	294	170	246	142	398	1656	987	381	394	810	815	542	549	654	639	335	504	349	274
ıs		*5*	*5*	*5*	*5*	*5*	*5*	*5*	*5*	*4*	*4*	*4*	*4*	*3*	*3*	*3*	*3*	*3*	*2*	‡	*2*	*2*	*2*	*2*	*1*	*1*	*1*	*1*	*1*	*1*	*1*	*1*
agena gracilis		—	0.003	—	0.004	—	—	—	—	0.008	0.004	0.009	0.018	0.003	0.006	0.008	—	—	0.001	0.005	—	0.013	0.007	0.014	—	0.007	0.012	0.009	0.003	—	—	0.004
	error (±)	—	<0.001	—	0.001	—	—	—	—	0.001	0.001	0.001	0.002	0.001	0.001	0.001	—	—	<0.001	<0.001	—	0.001	0.001	0.001	—	0.001	0.001	0.001	0.001	—	—	0.001
ı vitreola		—	0.002	0.026	—	—	—	—	—	—	—	—	—	—	—	—	—	0.010	0.003	—	—	0.003	—	0.001	—	—	—	0.003	—	0.003	—	—
	error (±)	—	<0.001	0.002	—	—	—	—	—	—	—	—	—	—	—	—	—	0.001	<0.001	—	—	<0.001	—	<0.001	—	—	—	<0.001	—	<0.001	—	—
decussata		—	—	—	0.006	—	—	—	—	0.002	0.002	0.001	—	—	—	—	—	—	—	0.001	—	—	0.007	0.010	—	0.005	—	0.003	—	—	—	—
	error (±)	—	—	—	0.001	—	—	—	—	<0.001	<0.001	<0.001	—	—	—	—	—	—	—	<0.001	—	—	0.001	0.001	—	0.001	—	<0.001	—	—	—	—
pseudoplicata		—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.003	0.001	—	—	—	—	—	—	—	—	—	—	—	—	0.007
	error (±)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	<0.001	<0.001	—	—	—	—	—	—	—	—	—	—	—	—	0.001
minuta		0.041	—	—	—	—	—	—	—	—	—	—	—	0.003	—	—	—	—	0.001	—	—	—	—	—	0.004	—	—	—	0.003	—	—	—
	error (±)	0.002	—	—	—	—	—	—	—	—	—	—	—	0.001	—	—	—	—	<0.001	—	—	—	—	—	0.001	—	—	—	0.001	—	—	—
ina reniforme		0.068	0.017	—	0.017	0.016	0.083	0.044	0.011	0.044	0.021	0.147	—	0.139	0.053	0.041	0.009	0.113	0.098	0.089	0.231	0.015	0.012	0.019	0.020	0.025	0.020	0.028	0.006	0.002	0.003	0.004
	error (±)	0.003	0.001	—	0.001	0.001	0.002	0.002	0.001	0.002	0.001	0.003	—	0.004	0.003	0.003	0.002	0.003	0.002	0.002	0.005	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	<0.001	0.001	0.001
a helenae		—	—	—	—	—	—	—	0.001	0.004	0.002	0.005	0.152	0.286	0.272	0.207	0.516	0.201	0.120	0.013	—	0.038	0.001	0.006	0.046	0.073	0.026	0.025	0.035	0.040	0.020	0.018
	error (±)	—	—	—	—	—	—	—	<0.001	0.001	<0.001	<0.001	0.005	0.006	0.008	0.006	0.012	0.004	0.002	0.001	—	0.002	<0.001	0.001	0.002	0.002	0.001	0.001	0.002	0.002	0.001	0.002
a norcrossi		0.099	0.002	0.003	0.094	0.084	0.019	0.071	0.069	0.024	0.062	0.075	0.013	0.102	—	0.012	0.035	0.030	0.005	0.001	0.052	—	0.006	0.011	0.122	0.051	0.014	0.039	0.114	0.027	0.037	0.018
	error (±)	0.004	<0.001	0.001	0.003	0.003	0.001	0.003	0.002	0.001	0.002	0.002	0.002	0.004	—	0.001	0.003	0.002	<0.001	<0.001	0.002	—	0.001	0.001	0.003	0.002	0.001	0.002	0.004	0.001	0.002	0.002
hia feylingi		0.003	—	0.003	0.006	—	0.001	—	0.014	0.030	0.004	0.016	0.058	0.014	0.047	—	—	0.015	0.008	0.016	0.021	0.068	0.042	0.118	0.013	0.064	0.410	0.407	0.058	0.264	0.209	0.153
	error (±)	0.001	—	0.001	0.001	—	<0.001	—	0.001	0.002	0.001	0.001	0.003	0.001	0.003	—	—	0.001	<0.001	0.001	0.001	0.003	0.001	0.002	0.001	0.002	0.005	0.005	0.003	0.004	0.005	0.005
lla elegantissima		0.007	0.002	0.013	0.011	0.006	0.006	0.017	0.017	0.018	0.002	0.015	0.013	0.010	0.053	0.077	0.065	0.015	0.253	0.027	0.239	0.063	0.166	0.084	0.214	0.078	0.005	0.009	0.057	0.028	0.026	0.036
	error (±)	0.001	<0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	<0.001	0.001	0.002	0.001	0.003	0.003	0.004	0.001	0.002	0.001	0.005	0.002	0.003	0.002	0.004	0.002	0.001	0.001	0.003	0.001	0.002	0.002
ina juncea		0.007	0.061	0.229	0.013	0.010	0.003	0.010	0.008	0.026	0.017	0.005	0.027	0.003	0.006	0.004	0.014	—	0.004	0.014	0.003	0.028	0.027	0.018	0.006	0.024	0.008	0.003	0.011	0.006	—	0.004
	error (±)	0.001	0.002	0.005	0.001	0.001	<0.001	0.001	0.001	0.001	0.001	<0.001	0.002	0.001	0.001	0.001	0.002	—	<0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	<0.001	0.001	0.001	—	0.001
ɜrina angulosa		0.020	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.002	—	—	0.003	—	0.001	—	0.002	0.002	—	0.003	—	—	—
	error (±)	0.002	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	<0.001	—	—	<0.001	—	<0.001	—	<0.001	<0.001	—	0.001	—	—	—
ɜrina fluens		0.034	0.048	0.105	0.002	0.004	0.001	—	—	—	—	0.003	—	—	—	0.004	—	—	—	0.002	—	0.020	0.023	0.031	0.006	0.027	0.006	0.009	—	—	—	—
	error (±)	0.002	0.002	0.004	<0.001	0.001	<0.001	—	—	—	—	<0.001	—	—	—	0.001	—	—	—	<0.001	—	0.001	0.001	0.001	0.001	0.001	0.001	0.001	—	—	—	—
ı laevicula		—	0.026	0.010	—	0.010	—	—	—	—	—	0.001	—	—	0.006	—	—	—	—	—	—	—	0.004	0.001	—	—	—	0.006	—	—	—	—
	error (±)	—	0.001	0.001	—	0.001	—	—	—	—	—	<0.001	—	—	0.001	—	—	—	—	—	—	—	<0.001	<0.001	—	—	—	0.001	—	—	—	—
nella pacifica		0.003	0.011	0.023	0.011	0.022	0.003	0.071	0.005	0.004	0.002	0.001	—	0.027	0.024	—	0.058	0.038	0.039	0.002	0.008	—	0.005	—	0.011	—	—	—	0.053	0.010	0.040	0.033
	error (±)	0.001	0.001	0.002	0.001	0.001	<0.001	0.003	0.001	0.001	<0.001	<0.001	—	0.002	0.002	—	0.004	0.002	0.001	<0.001	0.001	—	<0.001	—	0.001	—	—	—	0.002	0.001	0.002	0.002
nella vitrea		0.474	0.677	0.232	0.468	0.592	0.555	0.201	0.631	0.370	0.391	0.304	0.063	0.041	0.148	0.248	0.073	0.163	0.073	0.065	0.089	0.176	0.197	0.147	0.181	0.173	0.061	0.073	0.079	0.069	0.063	0.066
	error (±)	0.008	0.006	0.005	0.006	0.007	0.005	0.005	0.006	0.005	0.006	0.004	0.003	0.002	0.006	0.006	0.004	0.004	0.001	0.002	0.003	0.004	0.003	0.003	0.004	0.003	0.002	0.002	0.003	0.002	0.003	0.003
fletcheri		0.034	0.009	0.003	0.002	0.002	0.003	0.031	—	—	0.006	0.003	—	0.003	—	—	—	—	0.006	0.007	0.021	0.005	0.005	0.017	0.006	—	—	0.002	0.006	0.002	0.006	0.011
	error (±)	0.002	0.001	0.001	<0.001	<0.001	<0.001	0.002	—	—	0.001	<0.001	—	0.001	—	—	—	—	<0.001	0.001	0.001	0.001	<0.001	0.001	0.001	—	—	<0.001	0.001	<0.001	0.001	0.001
la digitata		—	—	—	—	—	—	—	—	0.004	—	0.003	0.004	—	—	—	—	—	—	—	—	0.005	0.004	0.002	—	0.004	0.030	—	—	—	—	—
	error (±)	—	—	—	—	—	—	—	—	0.001	—	<0.001	0.001	—	—	—	—	—	—	—	—	0.001	<0.001	<0.001	—	0.001	0.001	—	—	—	—	—
la stella		0.007	0.006	0.007	0.013	0.004	0.004	0.037	0.005	0.016	0.006	0.013	0.049	0.014	—	0.004	—	0.010	0.015	0.279	0.039	0.083	0.066	0.065	0.022	0.011	0.081	0.025	0.039	0.073	0.049	0.215
	error (±)	0.001	0.001	0.001	0.001	0.001	<0.001	0.002	0.001	0.001	0.001	0.001	0.003	0.001	—	0.001	—	0.001	0.001	0.003	0.002	0.003	0.002	0.002	0.001	0.001	0.002	0.001	0.002	0.002	0.002	0.005
lina labradorica		0.010	0.042	0.245	0.071	0.092	0.044	0.044	0.064	0.174	0.144	0.141	0.371	0.007	0.030	0.020	—	0.013	0.007	0.001	—	0.010	0.012	0.010	—	0.025	0.018	0.012	0.025	0.012	0.017	0.007
	error (±)	0.001	0.002	0.006	0.002	0.003	0.001	0.002	0.002	0.004	0.003	0.003	0.008	0.001	0.003	0.002	—	0.001	<0.001	<0.001	—	0.001	0.001	0.001	—	0.001	0.001	0.001	0.002	0.001	0.001	0.001
ion gallowayi		—	0.006	—	0.004	—	0.001	—	—	—	—	—	—	—	—	—	—	0.035	0.007	0.008	—	0.005	0.006	0.006	—	0.002	—	—	—	—	—	—
	error (±)	—	0.001	—	0.001	—	<0.001	—	—	—	—	—	—	—	—	—	—	0.002	<0.001	0.001	—	0.001	0.001	0.001	—	<0.001	—	—	—	—	—	—
frigida		0.096	0.016	0.013	0.074	0.059	0.031	0.041	0.017	0.018	0.039	0.019	0.013	0.034	0.065	0.089	0.129	0.073	0.146	0.208	0.092	0.065	0.052	0.035	0.044	0.055	0.011	0.012	0.019	0.004	0.012	0.015
	error (±)	0.004	0.001	0.001	0.002	0.002	0.001	0.002	0.001	0.001	0.002	0.001	0.002	0.002	0.004	0.004	0.006	0.003	0.002	0.003	0.003	0.003	0.002	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.001
hidium excavatum		0.055	0.014	0.010	0.094	0.063	0.190	0.255	0.103	0.061	0.148	0.103	0.040	0.306	0.183	0.264	0.079	0.241	0.206	0.096	0.194	0.138	0.138	0.061	0.293	0.256	0.145	0.132	0.398	0.325	0.335	0.332
	error (±)	0.003	0.001	0.001	0.003	0.002	0.003	0.006	0.002	0.002	0.003	0.002	0.003	0.006	0.006	0.006	0.005	0.005	0.002	0.002	0.004	0.004	0.003	0.002	0.005	0.004	0.003	0.003	0.007	0.005	0.006	0.007
hidium foraminosum		—	0.002	—	0.094	0.018	0.042	0.177	0.049	0.131	0.135	0.113	0.121	0.003	0.036	—	—	0.005	—	0.001	—	0.075	0.001	—	0.002	0.045	0.063	0.101	0.040	0.040	0.123	0.007
	error (±)	—	<0.001	—	0.003	0.001	0.001	0.005	0.002	0.003	0.003	0.002	0.005	0.001	0.003	—	—	0.001	—	<0.001	—	0.003	<0.001	—	<0.001	0.002	0.002	0.002	0.002	0.002	0.004	0.001
hidium hallandense		0.007	0.026	0.033	0.010	0.014	0.006	—	0.001	0.034	0.002	0.011	0.004	—	0.036	0.012	—	0.013	—	0.116	0.005	0.108	0.155	0.277	0.007	0.045	0.067	0.078	0.017	0.063	0.032	0.044
	error (±)	0.001	0.001	0.002	0.001	0.001	0.001	—	<0.001	0.002	<0.001	0.001	0.001	—	0.003	0.001	—	0.001	—	0.002	0.001	0.003	0.003	0.004	0.001	0.002	0.002	0.002	0.001	0.002	0.002	0.002

These results were used in the cluster analysis. Species proportions are recorded as decimal fractions. Calculated standard error (definition given in text) associated with each fractional abundance is also listed. (‡) — Sample whose population is probably reworked.

APPENDIX 2

List of all species encountered

Due to space considerations, species are listed with author name and year of publication only. In cases where the present generic designation differs from the original, the original genus name is provided in square brackets. (§) "Temperate" species, *i.e.* species that are recorded living south of the Aleutian Islands only. (¶) "Arctic" species, *i.e.* species that are recorded living north of the Aleutian Islands only. Unmarked species are cosmopolitan.

Angulogerina angulosa (Williamson), 1858, [*Uvigerina*].
Angulogerina fluens Todd, 1948.
Astrononion gallowayi Loeblich and Tappan, 1953.
§*Bolivina decussata* Brady, 1881.
Bolivina minuta Natland, 1938.
Bolivina pseudoplicata Heron-Allen and Earland, 1932.
Bolivinellina pacifica (Cushman and McCulloch), 1942, [*Bolivina acerosa* Cushman var.].
Botuloides pauciloculus Zheng, 1979.
Buccella frigida (Cushman), 1922, [*Pulvinulina*].
Bulimina gibba Fornasini, 1902.
Buliminella elegantissima (d'Orbigny), 1839, [*Bulimina*].
Cassidulina cf. *teretis* Tappan, 1951.
Cassidulina laevigata d'Orbigny, 1826.
¶*Cassidulina reniforme* Nørvang, 1945, [*Cassidulina crassa* d'Orbigny var.].
Cribroelphidium excavatum (Terquem), 1876, [*Polystomella*].
Cribroelphidium foraminosum (Cushman), 1939, [*Elphidium hughesi* Cushman and Grant var.].
Cribroelphidium hallandense (Brotzen), 1943, [*Elphidium*]. Synonym: *Elphidium subarcticum* Cushman, 1944.
§*Cribroelphidium microgranulosum* (Galloway and Wissler), 1951, [*Elphidium*]
Cushmanina striatopunctata (Parker and Jones), 1865, [*Lagena*].
Dentalina ittai Loeblich and Tappan, 1953.
§*Eilohedra laevicula* (Resig), 1958, [*Epistominella*].
Elphidiella arctica Parker and Jones, 1864.
Elphidiella hannai (Cushman and Grant), 1927, [*Elphidium*].
Eoeponidella pulchella (Parker), 1952. [*Pninaella*].
§*Epistominella pacifica* (Cushman), 1927, [*Pulvinulina*].
Epistominella vitrea Parker, 1953.
§*Euloxostomum alatum* (Seguenza), 1862, [*Vulvulina*].
Euuvigerina aculeata (d'Orbigny), 1846, [*Uvigerina*].
Euuvigerina juncea (Cushman and Todd), 1941, [*Uvigerina*].
Favulina hexagona (Williamson), 1848, [*Entosolenia*].
Favulina melo (d'Orbigny), 1839, [*Oolina*].
Fissurina cucurbitasema Loeblich and Tappan, 1953.
Fissurina eburnea (Buchner), 1940, [*Lagena*].
Fissurina fasciata (Egger), 1857, [*Oolina*].
Fissurina laevigata Reuss, 1850.
Fissurina lucida (Williamson), 1848, [*Entosolenia marginata* (Montagu) var.].
Fissurina marginata (Walker and Boys), 1784, [*Serpula*].
Fissurina serrata (Schlumberger), 1894, [*Lagena*].
Fissurina subquadrata Parr, 1945.
Fissurina vitreola (Buchner), 1940, [*Lagena*].
Galwayella trigonoelliptica (Balkwill and Millett), 1884, [*Lagena*].
§*Gavelinopsis campanulata* (Galloway and Wissler), 1927, [*Globorotalia*].
cf. *Glabratella arctica* Scott and Vilks, 1991.
Globobulimina auriculata (Bailey), 1851, [*Bulimina*].
§*Globocassidulina* cf. *bradshawi* (Uchio), 1960, [*Cassidulina*].
Globocassidulina subglobosa (Brady), 1881, [*Cassidulina*].
Homalohedra borealis (Loeblich and Tappan), 1954, [*Oolina*].
Homalohedra lineata (Williamson), 1848, [*Entosolenia*].
Homalohedra quasilineata Patterson, 1990.
Homalohedra williamsoni (Alcock), 1865, [*Entosolenia*].
¶*Islandiella helenae* Feyling-Hanssen and Buzas, 1976.
Islandiella norcrossi (Cushman), 1933, [*Cassidulina*].
Lagena dorseyae McLean, 1956.
Lagena fidicularia Patterson, 1993.
Lagena nebulosa Cushman, 1923.
Lagena semilineata Wright, 1886.
Lagena striaticollis (d'Orbigny), 1839, [*Oolina*].
Lamarckina haliotidea (Heron-Allen and Earland), 1911, [*Pulvinulina*].
Lobatula fletcheri (Galloway and Wissler), 1927, [*Cibicides*].
Lobatula lobatula (Walker and Jacob), 1798, [*Nautilus*].
§*Neoconorbina parkerae* (Natland), 1950, [*Discorbis*].
Nonionella digitata Nørvang, 1945, [*Nonionella turgida* (Williamson) var.].
§*Nonionella stella* Cushman and Moyer, 1930, [*Nonionella miocenica* Cushman var.].
Nonionellina labradorica (Dawson), 1860, [*Nonionina*].
Parafissurina lateralis (Cushman), 1913, [*Lagena*].
Parafissurina semicarinata (Buchner), 1940, [*Parafissurina lateralis* (Cushman) forma].
Patellina corrugata Williamson, 1858.
Procerolagena amphoriniformis (McCulloch), 1977, [*Lagena*].
Procerolagena complurecosta (Patterson), 1990, [*Lagena*].
Procerolagena distoma (Parker and Jones), 1864, [*Lagena*].
Procerolagena gracilis (Williamson), 1848, [*Lagena*].
Procerolagena gracillima (Seguenza), 1862, [*Amphorina*].
Procerolagena meridionalis Wiesner, 1931, [*Lagena gracilis* Williamson var.].
Procerolagena simulampulla Patterson, 1991.
Procerolagena wiesneri Parr, 1950, [*Lagena striata* (Montagu) var.].
Pseudononion basispinatum (Cushman and Stewart), 1930, [*Nonion pizarrensis* Berry var.]
§*Pullenia salisburyi* Stewart and Stewart, 1930.
Pygmaeoseistron hispidum (Reuss), 1863, [*Lagena*].
Quinqueloculina seminulum (Linné), 1758, [*Serpula*].
§*Rosalina columbiensis* (Cushman), 1925, [*Discorbis*].
Siphonaperta stalkeri (Loeblich and Tappan), 1953, [*Quinqueloculina*].
§*Spirosigmoilina tenuis* (Czjzek), 1848, [*Quinqueloculina*].
Stainforthia cf. *concava* (HËglund), 1947, [*Virgulina*].
Stainforthia feylingi Knudsen and Seidenkrantz, 1993.
Stetsonia minuta Parker, 1954.
Trochammina ex gr. *squamata* Parker and Jones, 1865.
Ventrostoma aff. *depressum* (Chaster), 1892, [*Lagena*].
Ventrostoma aff. *fovigerum* (Buchner), 1940, [*Lagena*].

APPENDIX 3

List of the 18 references used to compile modern distributions of foraminiferal temperate and Arctic shelf species at high latitudes

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