

# Plant macrofossil, pollen, diatom, and foraminiferal biofacies of the Fraser delta

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**Abstract:** The Fraser River delta plain supports a diverse array of marine and terrestrial ecological communities. A mosaic of marshes, sand flats, and mud flats in the intertidal zone and wet meadows, shrub lands, bogs, and riparian woodlands above the limit of tides can be linked by a successional model that relates ecological communities to elevation and substrate characteristics. Paleocological investigations of plant macrofossils, pollen, diatom, and foraminifers have proven useful in 1) reconstructing late-glacial and early Holocene conditions in the Strait of Georgia, 2) reconstructing small-scale changes in relative sea level, 3) assessing flood frequency, and 4) explaining autogenic changes related to fire occurrence in raised bogs on the delta plain.

**Résumé :** La plaine deltaïque du fleuve Fraser est l'habitat de communautés écologiques et terrestres d'une grande diversité. Un modèle successif qui met en corrélation les communautés écologiques avec l'altitude et les caractéristiques du substrat permet de relier la mosaïque des marécages, des estrans sableux et des estrans boueux de la zone intertidale aux prairies humides, aux broussailles, aux tourbières et aux boisés riverains qu'on observe au-dessus de la limite des marées. Les études paléoécologiques des macrofossiles de plantes, de pollens, de diatomées et de foraminifères se sont avérées utiles pour 1) reconstituer les conditions de la fin de la dernière glaciation et de l'Holocène précoce dans le détroit de Georgia, 2) reconstituer les changements à petite échelle du niveau marin relatif, 3) évaluer la fréquence des crues et 4) expliquer les changements autogènes liés aux feux de tourbières soulevées sur le territoire de la plaine deltaïque.

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## INTRODUCTION

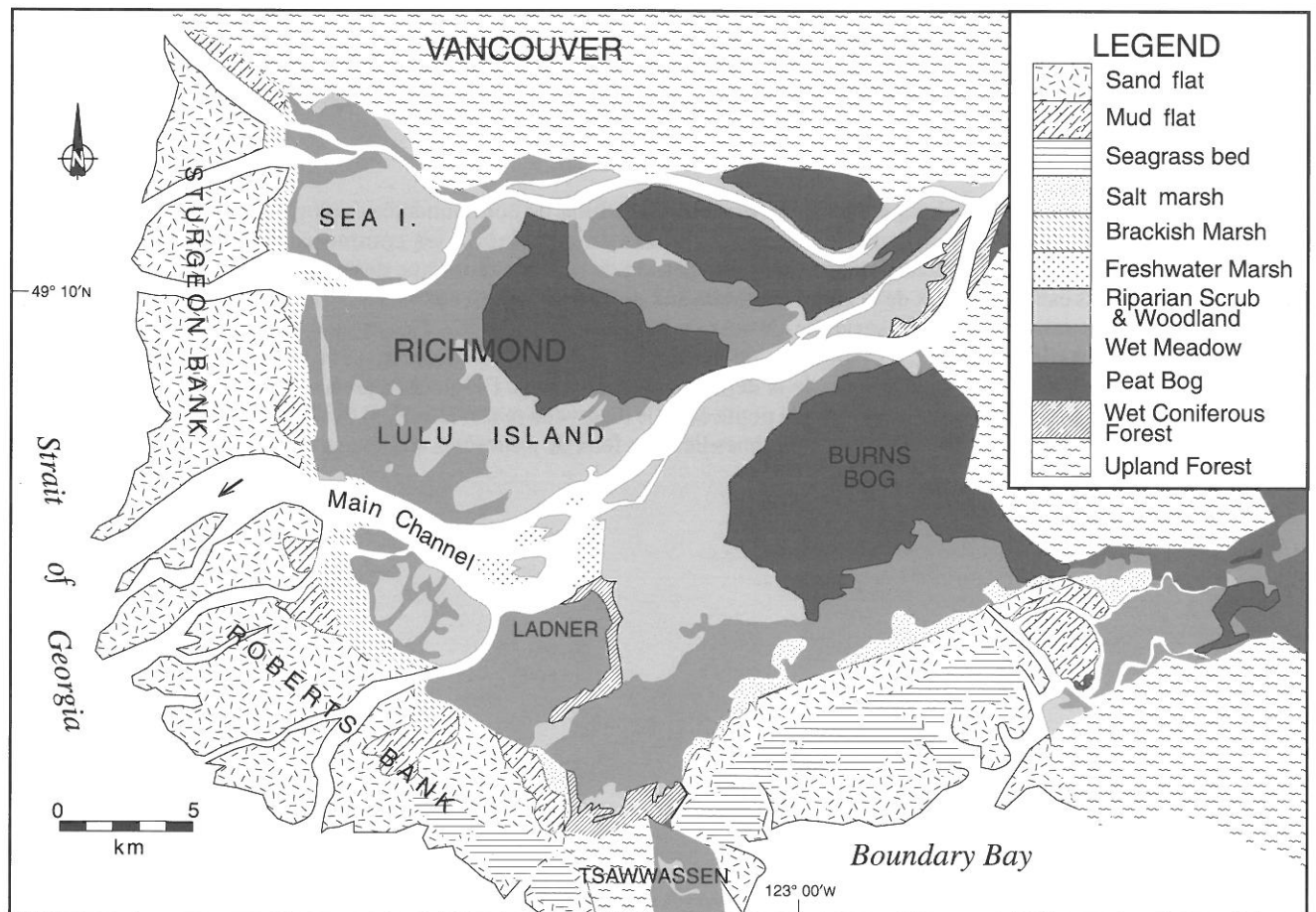
The Fraser River delta has been built out into the deep waters of the semienclosed marine basin of the Strait of Georgia during the Holocene Epoch (Luternauer et al., 1993). The delta now extends more than 20 km west from its apex near New Westminster and covers an area of about 1000 km<sup>2</sup> (Mathews and Shephard, 1962). The structure of the delta has been determined from onshore and offshore drilling and seismic surveys (Luternauer et al., 1993; Monahan et al., 1993). These geological and geophysical investigations have benefited from complementary and ancillary research on the paleoecology of the delta. In this paper we review these paleoecological investigations and assess their contribution to our understanding of the development of the Fraser delta.

Paleoenvironmental conditions are inferred from assemblages of fossil organisms using modern community-environment relationships. Although deltaic communities exhibit substantial local variation, their distribution is largely controlled by the elevation of the surface and the properties of the substrate. Progressive aggradation of the delta surface induces shifts in the distribution of ecological communities

and predictable changes in the structure of the community at a site. A model of successional change based on elevation-aggradation-community structure relationships can be used to analyze variations in paleoecological communities through time. Departures from the successional sequence predicted by the model may indicate unstable conditions associated with shifts in distributary-channel position or changes in sea level.

In this paper we present a simple successional model that can be used as a diagnostic tool in paleoecological research on the Fraser delta, and discuss the most important paleoecological studies that have been conducted there to date. We focus on vascular plants (macrofossils and pollen), diatoms, and foraminifers, which are the main fossil groups used in past paleoecological studies.

Although our focus is on the Fraser delta itself, it should be noted that paleoecological research in neighbouring areas can also contribute to a better understanding of the evolution of the Fraser delta. For example, variations in delivery of water and sediment to the delta front are linked to changes in the climate and vegetation of the Fraser River basin, which can be documented by paleoecological analysis. In addition,



**Figure 1.** Plant communities and associated habitats of the Fraser River delta in the early historical period; adapted from North and Teversham (1979).

changes in sea or land level, which strongly affect the rate of growth of the delta, can be documented through paleoecological study of the coastal margins of the Strait of Georgia.

## MODERN BIOTIC COMMUNITIES OF THE FRASER DELTA

The primary division of habitats in deltaic environments is between marine and terrestrial realms. The marine realm comprises the area below low tide, i.e. the subtidal zone. In morphological terms this is equivalent to the prodelta, the delta slope, and the lower delta plain. The ecological communities of the subtidal zone are often poorly known because of sampling difficulties.

The intertidal zone is the transitional area between the marine and terrestrial realms. The width of the intertidal zone in a deltaic environment is largely determined by the local tidal range. In the case of the Fraser River delta, the maximum tidal range is about 4 m (Milliman, 1980), and the intertidal zone is relatively broad (up to 7 km). Some 80% of this area consists of unvegetated sand and mud flats (Fig. 1). Parts of the upper subtidal zone and lower intertidal zone are occupied by beds of eelgrass (*Zostera* spp.), and the upper, vegetated part of the intertidal zone supports salt and brackish marsh communities. Intertidal marshes and tidal flats on the Fraser delta have undergone some disturbance in the last century as a result of river training, channel diversion, and construction.

The natural landscape above the high-water mark has been extensively altered in this century, but the distribution of natural biotic communities has been reconstructed from the field notes of the original land surveyors (North and Teversham, 1979). The vegetation map derived from these notes (Fig. 1) reveals a complex mosaic of aquatic, semiaquatic, and terrestrial plant communities: sloughs, freshwater marshes, wet meadows and shrub lands, bogs, and riparian forests. From a paleoecological perspective this map is very useful; it not only provides a typology of modern ecological communities, but also shows their relative extent and distribution.

Prior to settlement, wet meadows covered about 40% of the upper delta plain, bogs about 30%, shrub lands and riparian woodlands about 20%, and flowing-water ecosystems (distributary channels, sloughs) about 10%. Bogs dominated interdistributary areas on the eastern part of the delta, whereas wet meadows and riparian shrub communities were common to the west. Freshwater marsh occurred as ribbons along the margins of active channels and sloughs and as pioneer

communities on mid-channel bars. Coniferous forest was common on the channel banks, particularly near the apex of the delta.

Small differences in the elevation of the Fraser River delta plain, and related differences in tidal submergence, water-table depth, substrate salinity, and sediment mobility have given rise to a variety of deltaic habitats which support diverse ecological communities. These communities lie along a bifurcating successional sequence with more-or-less isolated endpoints (Fig. 2). The first steps in the successional series are undifferentiated prodelta and slope environments. These environments are succeeded by intertidal habitats. On the upper delta plain, we recognize a successional sequence associated with aggradation in poorly drained interdistributary areas, culminating in the development of oligotrophic raised bogs (Fig 50 in Hebda, 1977). An independent successional sequence is linked to aggradation on relatively well drained channel banks; this sequence passes from freshwater marsh, through riparian woodland, to wet coniferous forest (Fig. 2).

Organic materials produced in these communities may be preserved at the site of origin (autochthonous material) or they may be entrained by wind or water and deposited elsewhere (allochthonous material). Paleoecologists focus on those organic components that are abundant and readily identifiable, have high preservation potential, and display community structures that are strongly influenced by local environmental conditions. The taxa included in this paper (plant macrofossils, pollen, diatoms, and foraminifers) are widely used in Quaternary studies in coastal areas for these reasons (e.g. Scott and Medioli, 1986; Warner, 1990; Jonasson and Patterson, 1992). Generalized distributions of these taxa along a deltaic marine-terrestrial gradient are shown in Figure 3.

Paleoenvironmental reconstruction on the Fraser River delta has been made more difficult as a result of settlement. The paleoecologist can no longer examine pristine communities in order to determine environmental influences. Habitat alienation, the introduction of alien species, and urban and industrial pollution have drastically altered biotic assemblages on the Fraser delta in the last century. Because the relative abundance of species in present-day communities may not be the same as in their presettlement counterparts, the characterization of modern analogues requires careful sampling of native biofacies. The dominant species, and general ecological characteristics, of these native biofacies are described below.

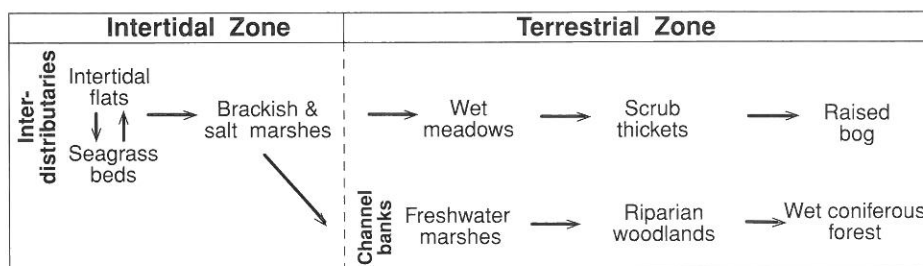


Figure 2.

Generalized successional pathways for plant communities on the Fraser River delta.

Realm	Habitat Type	Indicator Taxa	
		Autotrophs	Heterotrophs
Terrestrial	Wet coniferous forest	Plant microfossils pollen	Diatoms
	Bog		
	Riparian shrub & woodlands		
	Wet meadows		
	Freshwater marshes		
Intertidal	Brackish & salt marshes	Foraminifers	Arcellaceans
	Seagrass beds		
	Intertidal flats		
Marine	Subtidal		

**Figure 3.** Generalized distributions of taxa discussed in this paper. Solid lines indicate habitats where the taxa are abundant; broken lines indicate sparse populations. Autotrophs are capable of photosynthesis; heterotrophs feed on other organisms.

### Subtidal zone

The subtidal zone includes the slope of the Fraser delta and the floor of the southern Strait of Georgia to the west. The environment of this area is strongly influenced by the Fraser River, which supplies 80% of the total runoff to the Strait of Georgia, and by tides, currents, and winds which mix the water column (LeBlond, 1983). Substrates in the subtidal zone consist of mud derived from suspended material in the Fraser River plume and coarser grained material transported by sediment gravity flows down channels or valleys cut into the Fraser delta slope (Luternauer et al., 1983).

### Prodelta and delta-slope biofacies

Photosynthetic marine micrororganisms such as dinoflagellates and diatoms live as plankton in the surface waters of the Strait of Georgia. They cannot live in the low-light conditions of the prodelta environment, so the dinoflagellates and diatoms that are commonly found in prodelta sediments are all allochthonous, as are terrestrially derived pollen and spores (Dobell, 1976; Mathewes, unpublished data). Whereas the organic cell walls of pollen, spores, and dinoflagellates resist dissolution as they settle through the prodelta water column, diatom valves are constructed from silica and tend to dissolve in these silica-deficient waters (Sancetta, 1989). As a consequence, the diatom assemblage in prodelta sediments consists of only the most robust of the marine planktonic species, plus those brackish and freshwater species that survive transport in the Fraser River plume (Shim, 1977; Harrison et al., 1983).

The foraminiferal fauna in prodelta sediments, however, is largely autochthonous. This fauna is strongly influenced by the relatively low salinity conditions of the southern Strait of Georgia and by the texture of the substrate. The prodelta and lower delta slope encompass part of the '*Elphidium-Elphidiella*' biofacies which occurs at water depths of about 50 to 200 m (Cockbain, 1963). *Criboelphidium excavatum*, the dominant species in this assemblage (Cockbain, 1963), and the other important species of this biofacies, *Buccella frigida*, *Elphidiella nitida*, and *Nonionella stella*, are common in

relatively shallow marine waters along the entire west coast of North America (Culver and Buzas, 1985). Elements of this fauna are present, however, at greater depths elsewhere in the Strait of Georgia.

Fine-grained sediments in deep water have a more diverse and abundant foraminiferal fauna than sands of the upper delta slope (Williams, 1989). Rapid sedimentation and frequent slumping of the sands near the upper slope break inhibit establishment of foraminifer and diatom populations. Some delta-slope sediments, however, contain an abundance of allochthonous species reworked from tidal-flat, marsh, or channel-margin habitats and carried down the slope by sediment gravity flows (Evoy et al., 1993).

### Intertidal zone

The distribution of intertidal biota on the Fraser delta, as on other temperate deltas, is linked to the elevation of the tidal platform, which determines the extent to which marine organisms are subject to dessication, and terrestrial organisms to inundation. Other factors that influence the character of the biota are the salinity of inundating and interstitial waters and the texture, organic content, and redox status of the substrate.

At present, all Fraser River distributaries discharge onto the western delta front. As a consequence, the water covering Sturgeon and Roberts banks (Fig. 1) at high tide is relatively fresh, particularly during summer when the Fraser River is in flood. Surface salinities are commonly  $\leq 5\text{‰}$  when marsh plants are actively growing, and these marshes are dominated by sedges and grasses that are tolerant of weakly saline conditions (Fig. 4). Very small amounts of fresh water are discharged into Boundary Bay (Fig. 1) at the southern front of the delta. Waters on the tidal flats and marshes in this area are consequently much more saline ( $\sim 25\text{‰}$ ) during the growing season. High rates of evaporation in mid-summer can render infrequently inundated areas at higher elevations in the Boundary Bay marshes hypersaline ( $>35\text{‰}$ ). Because of their relatively high salinity, these marshes resemble true salt marshes in their species composition (Fig. 4).

The distribution of biota on the tidal flats themselves seems to be more controlled by substrate mobility than by salinity. We, therefore, discuss the tidal-flat environment in terms of the biofacies associated with sand- and mud-dominated substrates.

### Sand-flat biofacies

The sediment load of the Fraser River is extremely rich in sand-sized material (Milliman, 1980), consequently most of the Fraser delta intertidal platform is mantled by sand. With the exception of eelgrass beds, these areas are unvegetated, and the sandy substrate is mobile. The lower and middle tidal flats are floored by horizontally bedded, fine- to medium-grained sand, which is commonly bioturbated, and contains whole or fragmented shells. These clean sands grade into silty sands of the mid to upper tidal flats.



The seagrass ecosystem of the Fraser River delta consists of native eelgrass (*Zostera marina*), the exotic *Zostera japonica*, and minor ditch grass (*Ruppia maritima*). The most important of these species from a paleoecological point of view is *Z. marina* which grows abundantly on sand flats at subtidal to lower intertidal elevations (Fig. 4). It is common on southern Roberts Bank and in Boundary Bay where water turbidity is relatively low. Although the shoots and pollen of *Z. marina* may be redeposited by tides and waves, the rhizomes of this species have a high potential for in situ preservation, and are a potentially useful paleoelevation indicator.

The sand-flat diatom community consists of benthic species which grow attached to sand grains or eelgrass stems, and marine planktonic species. Sand-flat deposits on Sturgeon Bank contain a benthic diatom assemblage with brackish or brackish-marine affinities; *Amphora staurophora* is the most common species (Fig. 4). The diatom communities in Boundary Bay are more marine in character and strongly resemble sand-flat communities in the Pacific Northwest (Rao and Lewin, 1976; Hemphill-Haley, 1995) and elsewhere (e.g. Vos and de Wolf, 1993). *Achnanthes delicatula* is the most common benthic diatom in sands of the lower and middle intertidal zone in Boundary Bay (Fig. 4). Marine planktonic diatoms, which are abundant in the lower and middle intertidal zone in Boundary Bay, are less common in the muddy sands of the upper intertidal zone (Hutchinson et al., 1995).

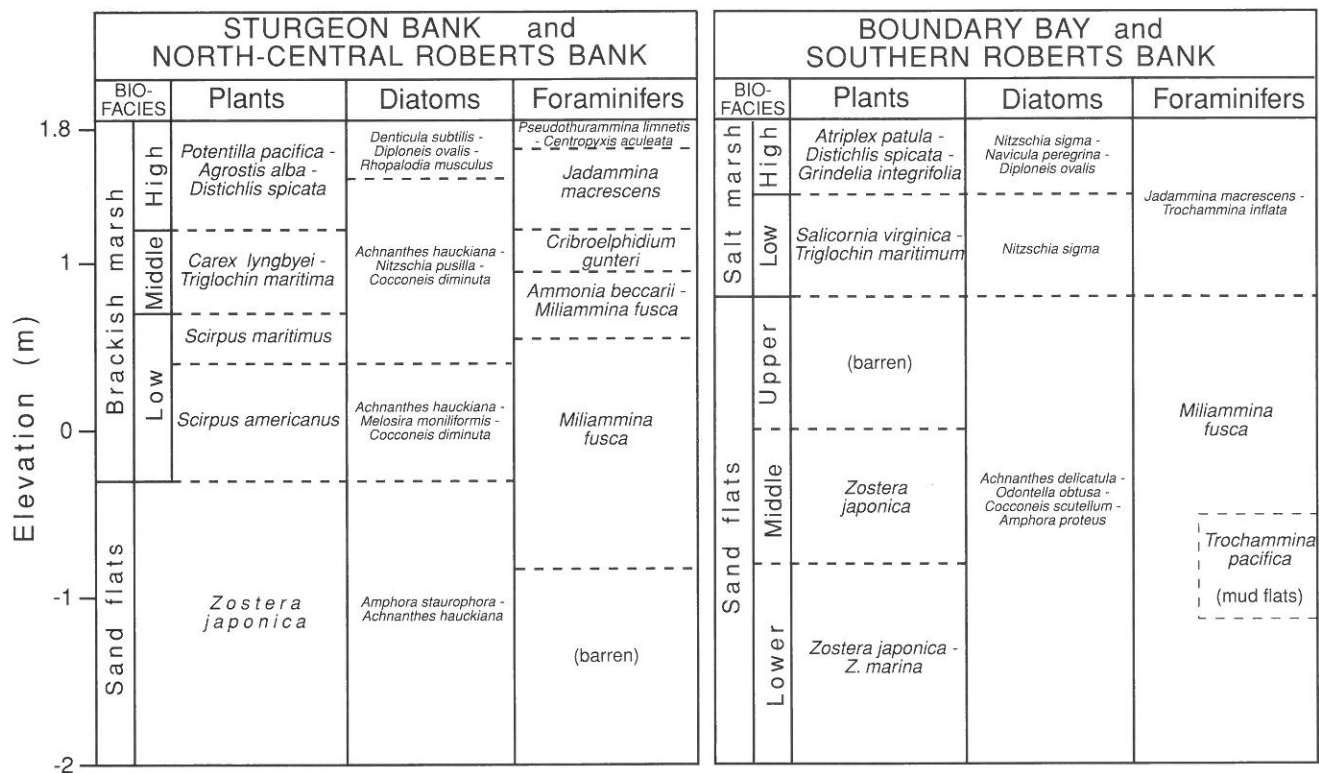
Allochthonous fresh and fresh-brackish species derived from distributary-channel margins and brackish marshes may be a significant component of these sand-flat assemblages.

Foraminiferal colonization of lower intertidal sand flats is inhibited by the unstable substrate. Except for allochthonous offshore and marsh foraminifers, and arcellaceans carried down from the high marsh, these sand flats are barren (Fig. 4). Sand flats at higher elevations, however, have a limited foraminiferal fauna dominated by *Milliammina fusca* (Williams, 1989; Patterson, 1990).

**Mud-flat biofacies**

Mud has accumulated on the western foreshore of the Fraser delta in sheltered locations. Diatom assemblages on the mud flats include many species that are found in sand-flat environments (Hutchinson, unpublished data), but tend to be dominated by species which prefer fine-textured substrates, such as *Navicula digitoradiata* (Laws, 1988).

Foraminiferal assemblages on the mud flats consist of virtually monospecific populations of *Trochammina pacifica* (Patterson, 1990). This biofacies is restricted to elevations between -1.1 and -0.5 m in areas stabilized by eelgrass. The dominance of *T. pacifica* is probably related to the organic-rich substrate in the upper marsh at the western front of the



**Figure 4.** Elevational ranges of key taxa in brackish (Sturgeon Bank and north-central Roberts Bank) and saline (Boundary Bay and southern Roberts Bank) areas of the intertidal zone on the Fraser delta. Sources: Shepperd (1981), Hutchinson (1982), Williams (1989), Patterson (1990), Baldwin and Lovvorn (1994), I. Hutchinson (unpublished data).

delta. This species is abundant in similar habitats elsewhere along the west coast of North America (Watkins, 1961; Bandy et al., 1965).

### Brackish-marsh biofacies

Because of the low ambient salinity, the brackish-marsh biofacies extends below mean sea level on the intertidal platform (Fig. 4). Several biotic zones with restricted elevation ranges are recognized on the basis of the relative abundance of various species of plants, diatoms, and foraminifers. In terms of plant distribution, there is a strong gradient in biodiversity with elevation. Low-marsh plant communities consist almost entirely of bulrushes (*Scirpus* spp.); high-marsh communities have a more complex and diverse structure (Hutchinson, 1982). Marsh-plant macrofossils, particularly rhizomes and leaf bases, have proven to be useful paleoelevation indicators on the Fraser delta (e.g. Styan and Bustin, 1983) and elsewhere in the Pacific Northwest (e.g. Atwater et al., 1995).

Diatom assemblages in brackish marshes of the Fraser delta have not been extensively investigated, but appear to consist of a diverse mix of benthic species, most with brackish affinities. Low- and middle-marsh assemblages are difficult to distinguish (Hutchinson, unpublished data), but high-marsh assemblages are relatively distinct (Fig. 4), consisting primarily of fresh-brackish species that can withstand dessication (aerophile species), such as *Navicula pusilla* and *Diploneis ovalis*. Similar diatom assemblages have been described at other estuaries in the Pacific Northwest (e.g. Hemphill-Haley, 1993, 1995; Nelson and Kashima, 1993).

Foraminiferal assemblages in brackish-marsh sediments on Sturgeon Bank were investigated by Williams (1989) and Patterson (1990). The lowest zone consists of a *Miliammina fusca* biofacies which extends from areas on the upper tidal flats stabilized by *Zostera japonica* into the low marsh. Similar foraminiferal assemblages have been described at equivalent elevations in other Northern Hemisphere temperate marshes (Lutze, 1968; Ellison and Nichols, 1976; Scott and Medioli, 1980; Scott et al., 1981; De Rijk, 1995).

*Miliammina fusca* is the dominant foraminifer on the upper sand flats and in the lower part of the low-marsh zone on both north-central Roberts Bank and Sturgeon Bank (Fig. 4). It is also common in the upper part of the low-marsh zone, where *Ammonia beccarii* is the dominant species. This faunal assemblage extends into the upper middle marsh, where *Criboelphidium gunteri* replaces *A. beccarii* (Patterson, 1990). As elsewhere, the low and middle marshes support substantial numbers of calcareous foraminifers (Phleger, 1965, 1966, 1970; Scott, 1976), but the tests of these species dissolve soon after death in the weakly acidic marsh sediments (Scott and Medioli, 1980).

The foraminiferal fauna of the high-marsh zone on Sturgeon and Roberts banks is dominated by *Jadammina macrescens*. The biofacies is similar to the high-marsh assemblage in brackish marshes in Nova Scotia (Scott and Medioli, 1980). *Pseudothurammina limnetis* and the arcellacean *Centropyxis aculeata* are common near the limit of tides. *Centropyxis aculeata* is an opportunistic species that can withstand

salinities up to 5‰ and much more hostile conditions than most other arcellaceans. The narrow vertical range of this biofacies makes it extremely useful for paleo-sea-level studies (Patterson et al., 1985; Guilbault et al., 1995).

### Salt-marsh biofacies

True salt marshes occupy the upper intertidal zone in Boundary Bay and at the western delta front near Tsawwassen (Fig. 1). The floristic character of the Boundary Bay salt marsh and its successional development have been described by Shepperd (1981). Accretion of mud and organic detritus on the tidal flats leads to the replacement of pioneering stands of arrowgrass (*Triglochin maritimum*) and pickleweed (*Salicornia virginica*) by high-marsh species such as saltgrass (*Distichlis spicata*) and gumweed (*Grindelia integrifolia*). Orache (*Atriplex patula*), an annual halophyte, is common at disturbed sites near the high-tide limit. Pollen in this environment is derived largely from local stands of chenopods (e.g. *Salicornia*), amaranths (e.g. *Atriplex*), and grasses (Hebda, 1977; Shepperd, 1981).

Diatom assemblages in the salt marshes are diverse; allochthonous marine species transported from subtidal and lower intertidal areas by winter storms (e.g. *Odontella* spp., *Cocconeis* spp., and *Amphora* spp.) commonly outnumber autochthonous species, particularly in areas where eelgrass detritus is deposited. The most common autochthonous species in the Boundary Bay salt marsh is *Nitzschia sigma* (Fig. 4). *Nitzschia terrestris* and *Denticula subtilis* are common in the marsh-upland transition zone.

Foraminiferal assemblages in the Boundary Bay salt marsh are similar to those of the high-marsh zone of the brackish marsh at Sturgeon Bank; the assemblages are dominated by *Jadammina macrescens* and include significant numbers of *Trochammina inflata*. Similar assemblages are widespread in other salt-marsh environments (e.g. Phleger, 1970; Scott, 1976).

### Terrestrial zone

#### Distributary-channel biofacies

Diatom assemblages in the modern Fraser River distributaries contain a mixture of planktonic and benthic freshwater species, with *Aulacoseira granulata* and *Achnanthes minutissima* respectively dominating these two groups (Beak Consultants, 1981; Hutchinson, unpublished data). The planktonic species may be autochthonous, but phytoplankton productivity in the distributaries is very low because of weak light penetration through the turbid water column (Harrison et al., 1983). In-channel diatom populations are therefore likely derived from the flushing of seasonal ponds and sloughs, and from the erosion of distributary-channel banks by floods.

#### Freshwater-marsh biofacies

Prior to settlement, freshwater marshes occupied the margins of all major distributary channels and the extensive network of sloughs that criss-crossed the Fraser delta (Ham, 1987).

The freshwater marshes that still remain are regularly submerged at high tide and are flooded for longer periods during the summer freshet. The vegetation at lower elevations in these marshes consists of bulrushes (*Scirpus* spp.) and sedges (*Carex* spp., *Eleocharis* spp.). Cattail (*Typha latifolia*), buckbean (*Menyanthes trifoliata*), and skunk cabbage (*Lysichiton americanum*) are common at higher elevations and also in freshwater marshes beyond the influences of tides (Bradfield and Porter, 1982). The pollen spectrum in these marshes is dominated by regional arboreal species; sedge, grass, and skunk cabbage are important secondary elements (Williams and Hebda, 1991).

The common diatoms in freshwater marshes are the same as those found in high brackish marshes; *Denticula subtilis*, *Diploneis ovalis*, *Pinnularia lagerstedtii*, and *Navicula cryptocephala* are the most abundant taxa (Hutchinson, unpublished data). Arcellacean faunas replace foraminifers in freshwater marshes. Not enough research has been carried out to define diatom and arcellacean assemblages in the various subenvironments of this habitat.

### Riparian-woodland biofacies

Channel banks above the freshwater marsh are occupied by riparian woodlands dominated by red alder (*Alnus rubra*), black cottonwood (*Populus trichocarpa*), Sitka spruce (*Picea sitchensis*), and willow (*Salix* spp.), with a well developed shrub understorey consisting of salmonberry (*Rubus spectabilis*) and red-osier dogwood (*Cornus stolonifera*) (Williams and Hebda, 1991). Inorganic sediment and allochthonous organic detritus are deposited in these woodlands during floods. Arboreal species dominate the pollen spectrum (Williams and Hebda, 1991), suggesting a mainly local source, but diatom assemblages are equivalent to those from freshwater marshes, and may be dominantly allochthonous (Hutchinson, unpublished data).

### Wet-meadow and shrub-land biofacies

Large areas of the western and southern Fraser delta plain were seasonally flooded grasslands before agricultural clearing and drainage destroyed this habitat (North and Teversham, 1984). The diatom biofacies of this environment is dominated by freshwater aerophilic species such as *Navicula mutica* (Hutchinson et al., 1995). Freshwater planktonic species which colonize seasonal ponds on the upper delta plain (e.g. *Aulacoseira* spp.) may be a minor component of this assemblage.

### Raised-bog biofacies

Peat bogs are the end member of the interdistributary successional pathway on the Fraser delta (Fig. 2). They develop in distal areas of the upper delta plain, beyond the limit of tides, where low rates of clastic sedimentation allow *Sphagnum* moss to become established as ground cover. The mat of *Sphagnum* restricts water flow and acidifies the substrate. Freshwater marsh species are quickly replaced by Ericaceae (e.g. Labrador tea, *Ledum groenlandica*), which are tolerant

of wet acidic soils and low nutrient supply (Hebda, 1977). Variable growth of *Sphagnum* around the base of shrubs produces a hummocky bog surface; higher areas may then be colonized by lodgepole pine (*Pinus contorta*) and birch (*Betula* spp.). These communities undergo complex successional changes linked to fire, the hummock-hollow cycle, and increased elevation of the bog surface (Hebda, 1977; Styan and Bustin, 1983). Slow decomposition of organic matter in this wet and acidic environment promotes peat accretion and the development of a raised bog; some of the bogs on the Fraser delta have achieved elevations of more than 5 m.

The pollen spectrum in Fraser delta bogs is dominated by pine, Ericaceae, and alder (Hebda, 1977). Birch pollen and bracken (*Pteridium*) spores are locally abundant in better-drained areas at bog margins. Few diatoms can survive in this highly acidic environment; consequently, diatom assemblages are generally sparse and have low biodiversity. The main species are acidophilic and include *Pinnularia divergentissima* and *Eunotia* spp. (Hutchinson, unpublished data).

## LATE QUATERNARY BIOFACIES

Late Pleistocene and Holocene macrofossil, pollen, diatom, and foraminiferal assemblages of the Fraser delta have been described from samples collected from cores and exposures. In this section, we review several studies in which the description of these assemblages has resulted in an improved understanding of depositional environments and environmental interactions. Pleistocene and early Holocene

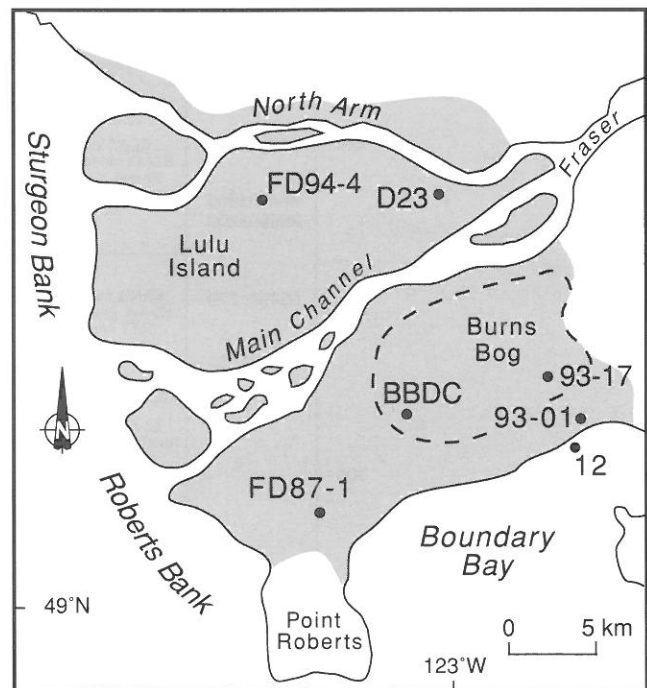


Figure 5. Location of cores discussed in the paper; shaded area is the Fraser delta.





depositional environments have been assessed from an analysis of pollen and foraminifers in two long cores, FD87-1 (367 m) and FD94-4 (304 m) (Fig. 5; Patterson and Cameron, 1991; Patterson and Luternauer, 1993; Mathewes, unpublished data). Middle and late Holocene environments, particularly on the southern delta, have been reconstructed from pollen and diatom assemblages in many short cores (Shepperd, 1981; Styan and Bustin, 1983; Clague et al., 1991; Williams and Hebda, 1991; Hutchinson et al., 1995).

**Pleistocene biofacies**

Two major predeltaic foraminiferal biofacies have been identified in cores FD87-1 and FD94-4: a cassidulinid-dominated assemblage found in the basal parts of both cores; and a *Criboelphidium barletti* biofacies found only in FD87-1 (Fig. 6).

The cassidulinid-dominated biofacies, found in diamicton and clayey sediments between 347.5 and 367 m in core FD87-1 and between 284 and 287 m in core FD94-4, is dominated by *Cassidulina reniforme*. This species lives in

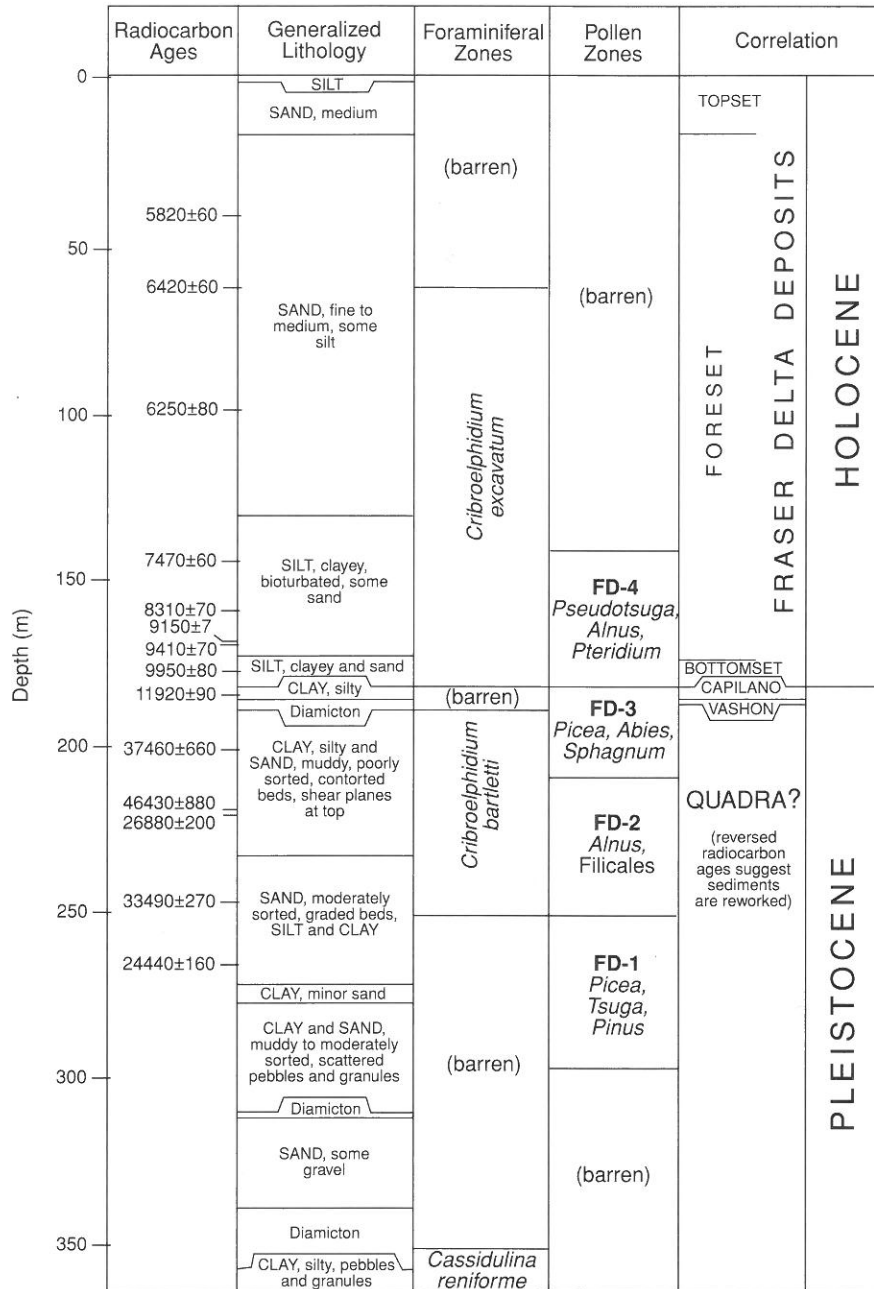


Figure 6. Stratigraphy and biofacies, core FD87-1.



ice-proximal glaciomarine environments (e.g. Bahnson et al., 1974; Elverhøi et al., 1980; Osterman, 1984) and has been reported from similar late-glacial environments in eastern Canada (Sejrup and Guilbault, 1980; Scott et al., 1989) and British Columbia (Patterson, 1993; Patterson et al., 1995). The present-day and paleodistributions of the major taxa of this biofacies indicate deposition in cold saline ( $\geq 27\text{‰}$ ) water approximately 100–200 m deep (Guilbault, 1980, 1989). The sediments containing this biofacies may correlate with the Semiahmoo Drift of Early Wisconsin age (Armstrong, 1975), but they could also be older.

The *Criboelphidium bartletti* biofacies occurs between 192.9 and 256 m in core FD87-1 in silt and clay which are continuous with underlying barren sediments. *Criboelphidium bartletti* has been recorded in shallow marine sediments (<150 m water depth) at high latitudes (Loeblich and Tappan, 1953; Todd and Low, 1967; Smith, 1970; Bergen and O'Neil, 1979).

Of the 35 sediment samples selected for analysis of pollen and spores from core FD87-1, only those samples between 140 and 300 m depth contained enough palynomorphs for quantitative analysis. Four pollen assemblage zones (FD-1 to FD-4) were identified in this interval based on abundances of characteristic taxa (Fig. 7). Although some of the pollen and spores were likely reworked from older deposits, the four pollen zones appear to correlate with the geological units in the core.

FD-1 (*Pinus-Picea-Tsuga* zone, 250–300 m) represents the first sediments that contain enough palynomorphs for quantitative analysis. The abundance of tree pollen suggests at least a partially forested landscape during this interval. Pollen zones FD-2 (*Alnus-Filicales* zone, 210–250 m) and the lower part of FD-3 (*Picea-Abies-Sphagnum* zone, 180–210 m) span the interval of the *C. bartletti* biofacies. Reversals in radiocarbon dates render the age of these deposits problematical (Fig. 6) and suggest that much of this material may be reworked.

The upper part of the FD-3 pollen zone (Fig. 7) is reliably dated to the period from 12 000 to 10 000  $^{14}\text{C}$  yr B.P. (Fig. 6). Although some of the material in these late Pleistocene deposits is reworked, the relatively high abundances of pine, alder and spruce pollen (Fig. 7) match pollen spectra from other late-glacial deposits in the region (Heusser, 1973).

## Holocene biofacies

### Prodelta and delta-foreslope biofacies

Prodelta and lower delta-slope muds contain a low-diversity foraminiferal fauna dominated by *Criboelphidium excavatum*, *Buccella frigida*, and *Elphidiella hannai* (Fig. 6; Patterson and Cameron, 1991; Patterson and Luternauer, 1993). This biofacies is found at depths of 67 to 180 m in core FD87-1 and 65 to 120 m in core FD94-4, similar to the depth at which it occurs in the present-day marine environment. *Criboelphidium excavata*, which dominates this assemblage, is widely distributed at shallow depths in temperate and polar seas at the present (Phleger, 1952; Loeblich and Tappan, 1953; Miller et al., 1982). It is also common in late Pleistocene

glaciomarine deposits, constituting 50–80% of the foraminiferal fauna (Feyling-Hanssen, 1976; Knudsen, 1976; Osterman, 1984; Rodriguez and Richard, 1986; Hald and Vorren, 1987; Patterson, 1993; Patterson et al., 1995). Its presence in temperate environments indicates a salinity below that of standard sea water (35‰).

There are several forms of *C. excavatum*, but only the 'clavatum' variant has been found in Fraser delta deposits dating from the early and middle Holocene. This form is indicative of either cold, normal-salinity marine waters (sometimes described as a 'warm ice-margin fauna'; Scott et al., 1989), or waters with slightly reduced salinities (Miller et al., 1982). The greater abundance of *C. excavatum* in early postglacial deposits, and the dominance of the 'clavatum' form, suggest that water temperature (and/or salinity) in the Strait of Georgia was somewhat lower during the early Holocene than at present.

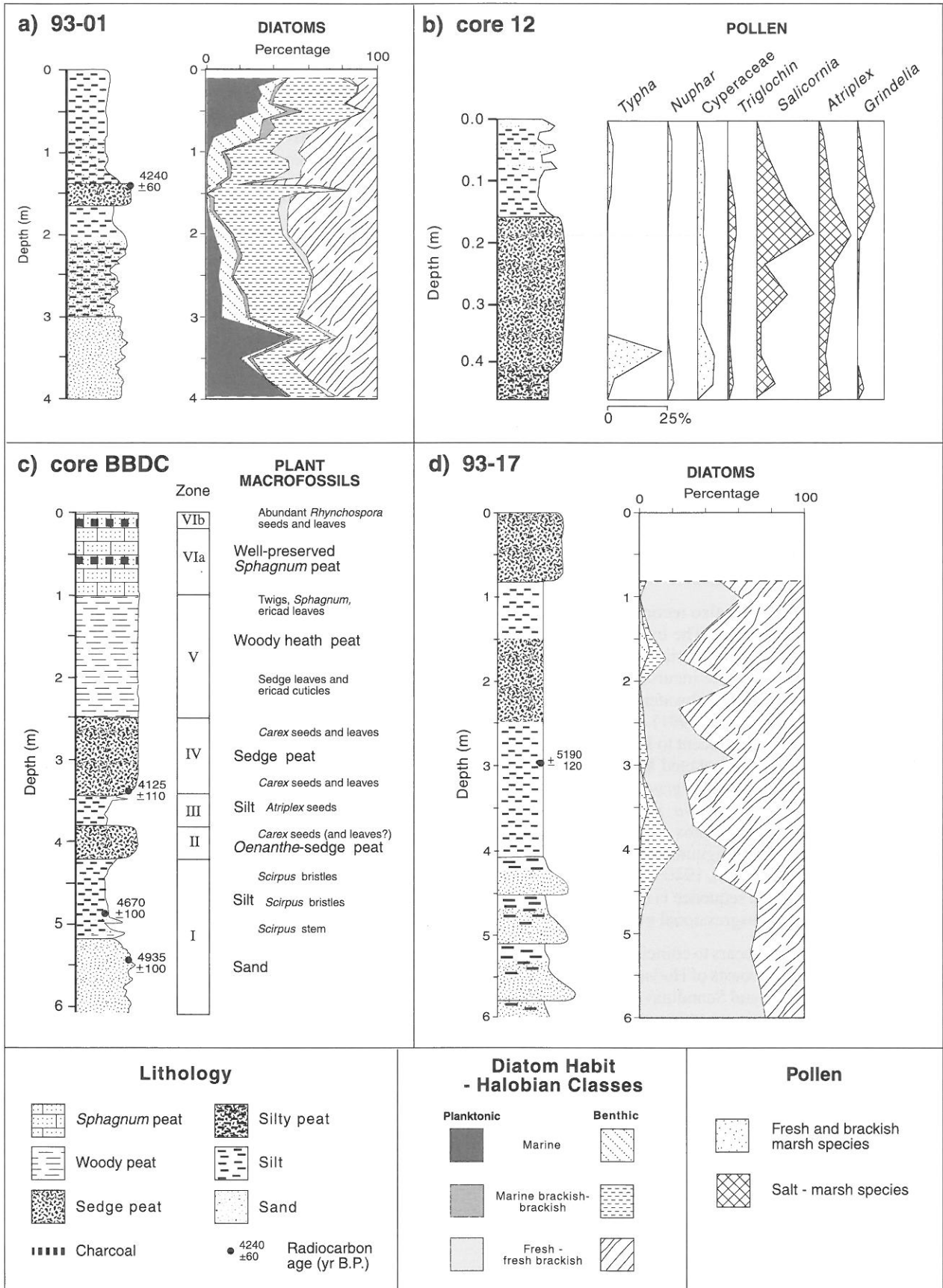
The conclusion that the regional climate was cooler in the early Holocene is, however, at odds with the paleoclimatic reconstruction based on the pollen record. Pollen zone FD-4, which correlates with the lower part of the *C. excavatum* zone, is characterized by large amounts of Douglas-fir (*Pseudotsuga menziesii*) and red alder pollen, and bracken spores (Fig. 7). This assemblage is typical of early Holocene pollen assemblages at other sites in southwestern British Columbia (Heusser, 1983; Mathewes, 1985) and western Washington (Heusser, 1977), which have been interpreted as indicating a warmer and drier climate than at present (Mathewes 1985; Cwynar, 1987). This being the case, one might expect higher surface temperatures in the Strait of Georgia at that time.

Foraminifers become increasingly less common higher in the delta-slope sequence and are absent in upper-slope, channel, and tidal-flat sands (Patterson and Cameron, 1991; Patterson and Luternauer, 1993). As mentioned previously, the high mobility of these sandy sediments curtails foraminiferal colonization. Foraminifers generally disappear at about 20 to 30 m depth in cores, but the range is from as little as 10 m in core FD91-1 to over 70 m in cores FD87-1 (Fig. 6) and FD88A-1 (Patterson and Cameron, 1991; Patterson and Luternauer, 1993).

### Tidal-flat and intertidal-marsh biofacies

A buried peat bed, which crops out on the foreshore of Boundary Bay (Fig. 8a; Kellerhals and Murray, 1969; Shepperd, 1981; Styán and Bustin, 1983), was laid down in a

**Figure 8.** Stratigraphy and plant macrofossil and microfossil assemblages of selected short cores from the Fraser River delta (core sites shown in Fig. 5): **a**) major diatom groups in core 93-01, from Hutchinson et al. (1995); **b**) selected pollen types, core 12; adapted from Shepperd (1981); **c**) biozones and plant macrofossils, core BBDC, adapted from Hebda (1977); **d**) major diatom groups, core 93-17, from Hutchinson et al. (1995). Figures 8a and 8d are reproduced with permission of the National Research Council of Canada.





brackish-freshwater marsh environment after the abandonment of distributary channels on the southern flank of the delta about 5000 years ago (Hutchinson et al., 1995). Underlying and overlying clastic sediments are tidal-flat deposits.

A typical tidal-flat aggradational sequence in the Boundary Bay foreshore area is found in the lower part of core 93-01 (Fig. 5, 8a). A basal sand unit contains high percentages of marine planktonic and brackish-marine benthic diatoms (Fig. 8a; Hutchinson et al., 1995). The marine planktonic component steadily decreases through the overlying, interbedded sandy muds which were deposited in the middle and upper intertidal zone, and benthic brackish species such as *Nitzschia levidensis* become dominant. Pollen of freshwater aquatic plants (e.g. *Typha* and *Nuphar*) (Fig. 8b; Shepperd, 1981), fern spores (Shepperd, 1981), and fresh-brackish diatoms (Fig. 8a) are abundant in the lower part of the peat, indicating succession to a freshwater-marsh environment.

Abundant sedge macrofossils in the middle of the peat (Styan and Bustin, 1983) herald the return of brackish marsh conditions, and mark the onset of a short-lived oscillation in sea level at around 4200 <sup>14</sup>C years BP. The transgression phase of this oscillation is recorded by an increase in the pollen of salt-marsh plants in the upper part of the peat (Fig. 8b), the subsequent transition to muddy sands, and the gradual increase in marine and marine-brackish diatoms in these sands and the overlying silts (Fig. 8a).

This sea-level oscillation is also recorded in core BBDC from western Burns Bog (Fig. 5). The transition from freshwater peats (Fig. 8c: zone II) to peaty silts containing *Atriplex* seeds (zone III) marks the marine incursion (Hebda, 1977). The silts in turn are overlain by freshwater peats, signalling a marine regression. Clague et al. (1991) recorded a similar sequence in a core from a site adjacent to BBDC. The silt unit in this core, which was also bracketed by peats, contained intertidal diatoms (e.g. *Navicula peregrina*) and foraminifers (*Miliammina fusca*, *Trochammina inflata*). Silts with brackish-marine pollen and diatoms overlying freshwater sedge peats and underlying sphagnum peats are also known from central Lulu Island (Hansen, 1940; Hutchinson, unpublished data). The Lulu Island sequence is undated, but the silt unit may mark the same transgression event.

This marine incursion appears to coincide with a sea-level oscillation identified on the coasts of Hudson Bay (Fairbridge and Hillaire-Marcel, 1977) and Scandinavia (Mörner, 1980). The effects of this transgression may have been magnified on the southern front of the Fraser delta by the contemporaneous closure of the distributary-channel network in this area (Hutchinson et al., 1995).

### Distributary-channel biofacies

Core 93-17 from eastern Burns Bog (Fig. 5) records a distributary paleochannel in the final stages of abandonment (Fig. 8d). Cyclic, fining-upward, sand-silt sequences in the lower part of the core were deposited by floods from a nearby channel. These sediments contain a meagre diatom assemblage composed largely of abraded valves of *Aulacoseira granulata*, a robust planktonic diatom which can withstand

fluvial transport (Hutchinson et al., 1995). Closure of the channel is indicated by increased deposition of fines and organics in the upper part of the core (Fig. 8d). These sediments have high concentrations of diatoms, mainly benthic freshwater species associated with shallow, standing water or wet substrates. Whereas diatom biofacies in abandoned channel deposits at upstream sites such as 93-17 are characterized by freshwater species, biofacies from sites closer to the channel mouth have high frequencies of brackish and marine diatoms (Hutchinson et al., 1995).

### Freshwater-marsh, wet-meadow, and riparian-woodland biofacies

Fluvial overbank deposits of the upper delta plain and their associated pollen biofacies have been described by Williams and Hebda (1991) from a 15 m vibracore (D23; Fig. 5) from central Lulu Island. A thin, basal, tidal-flat sand is overlain by silts containing skunk cabbage, sedge, and grass pollen, and horsetail spores. The inferred vegetation is similar to the present-day vegetation in freshwater marshes on the upper delta plain. Abundant pollen of herbaceous species and low-shrub pollen indicate that the site was frequently flooded by the Fraser River at this time. A zone with significant shrub pollen (sweet gale (*Myrica gale*), Ericaceae, and Rosaceae) overlies the freshwater marsh deposit. Williams and Hebda (1991) inferred that this change from marsh to swamp occurred because the site had aggraded to a higher elevation and was less subject to flooding. The successional sequence outlined in Figure 2 suggests that the swamp would in time be replaced by a raised bog, but increases in red alder and skunk cabbage pollen higher in the sequence indicate that the area became a riparian woodland. The site was again being flooded frequently, either in response to a rise in base level or a shift in the position or discharge of a nearby distributary channel.

### Raised-bog biofacies

The upper half of core BBDC (Fig. 8c) records a typical raised bog succession on the Fraser delta (Hebda, 1977). The salt-marsh or upper tidal-flat deposits of zone III are overlain by peat deposited in a freshwater sedge marsh or fen (zone IV). The fen deposits, in turn, are overlain by heath shrubland peat (zone V). The heath habitat was gradually colonized by *Sphagnum* mosses and Ericaceae species characteristic of a bog environment. The uppermost unit (zone VI) consists almost entirely of *Sphagnum* peat. This sequence follows the successional path in interdistributary areas shown in Figure 2.

Changes in plant macrofossils and pollen in zone VI illustrate the role of fire in mediating the development of the *Sphagnum* hummock-hollow cycle (Hebda, 1977, fig. 7). Large fires in the bog are recorded by charcoal layers in the peat (Fig. 8c). These fires destroy higher, drier moss hummocks and the heath plants that grow on them. Reduced growth of peat in these patches converts them to wet acid hollows, which are colonized by sedges (e.g. *Rhynchospora*). Peat deposition is rapid in these wet microenvironments which subsequently regenerate into *Sphagnum* hummocks.

## DISCUSSION AND CONCLUSIONS

A reconstruction of the natural landscape of the Fraser delta in the early historical period reveals a mosaic of wet meadows and shrub lands, bogs, and riparian woodlands above the limit of tides, and marshes, sand flats, and mud flats in the intertidal zone. These environments can be linked by a successional model that relates ecological communities to elevation and the character of the substrate.

Intertidal and subtidal habitats on the Fraser delta have changed in the last century, due to human activity, but the ecological structure of these communities, prior to settlement, has been determined with some confidence from their modern counterparts. In contrast, most of the natural vegetation of the upper delta plain has been lost, making the task of the paleobotanist or palynologist difficult. Present-day plant communities on the delta plain may not provide good analogues for their prehistoric counterparts, and surface pollen collections may bear little resemblance to pollen spectra from earlier times. Despite these problems, there is sufficient baseline information on the distribution and character of modern biofacies to at least identify paleobiofacie

Plant macrofossils play an important role in these investigations, not only as raw materials for AMS radiocarbon dating, but also as indicators of the ambient physical environment and plant-community composition. Together with pollen, spores, diatoms, and foraminifers, plant macrofossils (including detrital wood and buried stumps) provide information on past environmental conditions such as climate, water depth, temperature, and salinity, and the relative elevation of the site.

The examples discussed in this paper demonstrate that some progress has been made in reconstructing paleoenvironmental change on the Fraser delta. We have shown the value of paleoecological investigations in 1) reconstructing late-glacial and early Holocene conditions in the Strait of Georgia (core FD87-1); 2) reconstructing small-scale marine transgressions and regressions (cores BBDC, 12, and 93-01); 3) assessing flood frequency in inter-distributary areas (core D23); and 4) developing models to explain autogenic changes associated with fire occurrence in raised bogs (core BBDC).

These paleoecological investigations are primarily reconnaissance studies focusing on changes in particular macro- or microfossil assemblages in local areas on the Fraser delta. A synthesis of the development of the Fraser delta's ecological mosaic can only be achieved if future workers link species and community responses to deltaic processes via integrated geological-paleoecological analyses. This approach is exemplified by the analysis of paleoseismic activity in southwestern British Columbia by Mathewes and Clague (1994), and on the Fraser delta by Clague et al. (1998).

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