AN INVESTIGATION OF THE HOLOCENE POLLEN RECORD FROM THE GREY ISLANDS, NEWFOUNDLAND

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AN INVESTIGATION OF THE HOLOCENE POLLEN RECORD FROM THE GREY ISLANDS, NEWFOUNDLAND

by

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A thesis submitted to the School of Graduate
Studies in partial fulfillment of the
requirements for the degree of
Master of Science

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ABSTRACT

An Investigation of the Holocene Pollen Record from the Grey Islands, Newfoundland

An 800 cm core from a lake (104 m; 50°46.08'N, 55°31'W) on the Grey Islands, situated in the Labrador Sea 20 km east of Newfoundland's Northern Peninsula, provides a nearly complete Holocene pollen sequence with a distinct maritime influence. By 9800 BP (705 cm), the site had emerged from the postglacial Daly Sea and a herb-shrub tundra was established. Tundra persisted until 7800 BP when spruce and fir invaded to form boreal forest. Fire at 7300 BP resulted in a brief resurgence of herbs and shrubs, primarily alder, followed by forest re-establishment by 6800 BP. Paludification led to an increase in *Sphagnum* and greatly decreased pollen influx after 3000 BP, followed by an increase in shrubs and herbs at the expense of trees after 1000 BP. Today the Grey Islands are dominated by tuckamore (dwarf shrub barrens) with patchy areas of black spruce forest and sphagnum bog.

Timing of initial forest development at the expense of shrub tundra (7800 BP) coincides with other sites on the Northern Peninsula, though as much as 1 ka later than the rest of the island and slightly earlier than in southeastern Labrador. Increasing tree birch between 7000 and 4500 BP is indicative of higher summer temperatures and a longer growing season, while also signalling the weakening of a cold ocean influence which, in pollen and dinoflagellate cyst records from the Labrador sea, is dated about 7000 BP. A major forest fire in the record falls within the 8000 to 6500 BP period of increased fire frequency on the Northern Peninsula. Water temperature in the Labrador

Sea reached a maximum around 6000 BP, coincident with the start of the hypsithermal period on the Grey Islands. After 2500 BP the Labrador Sea re-exerted a cold bottom water influence and the Grey Islands experienced paludification and forest demise.

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CHAPTER 1 INTRODUCTION

The physical landscape of North America was transformed during the course of the Pleistocene glaciations, resulting not only in a geomorphically altered landscape, but also in the displacement of plant species and vegetation patterns. Following the late Wisconsinan glaciation and postglacial emergence, the land was free to begin a phase of primary succession and recolonization. The migration and establishment of postglacial plant communities eventually led to the modern distribution of vegetation zones and plant taxa in North America.

The following study is a palynological investigation of the Late Quaternary vegetation history of the Grey Islands, Newfoundland. In comparison to the mainland portion of eastern Canada, there remain many gaps in Newfoundland's palynological record and this study adds to our knowledge of postglacial vegetation in northern-northwest Newfoundland. The Grey Islands site is unique in its situation on a small island in the Labrador Sea. This site may be less affected than others in the region by pollen input from the continent to the west, and thus provide a relatively clean record of postglacial vegetation on the Northern Peninsula. The study site's maritime setting provides an additional opportunity to document Holocene vegetation history under the influence of changing thermal and oceanographic conditions in the Labrador Sea and their effect upon the adjacent terrestrial environment.

The Grey Islands (50°54'N, 55°36'W) are located north of White Bay in the Labrador Sea, and are situated approximately 20 km east of Newfoundland's Great

Northern Peninsula (Fig. 1.1). They are comprised of several offshore rocks and shoals along with two large islands, Bell Island and Groais Island.

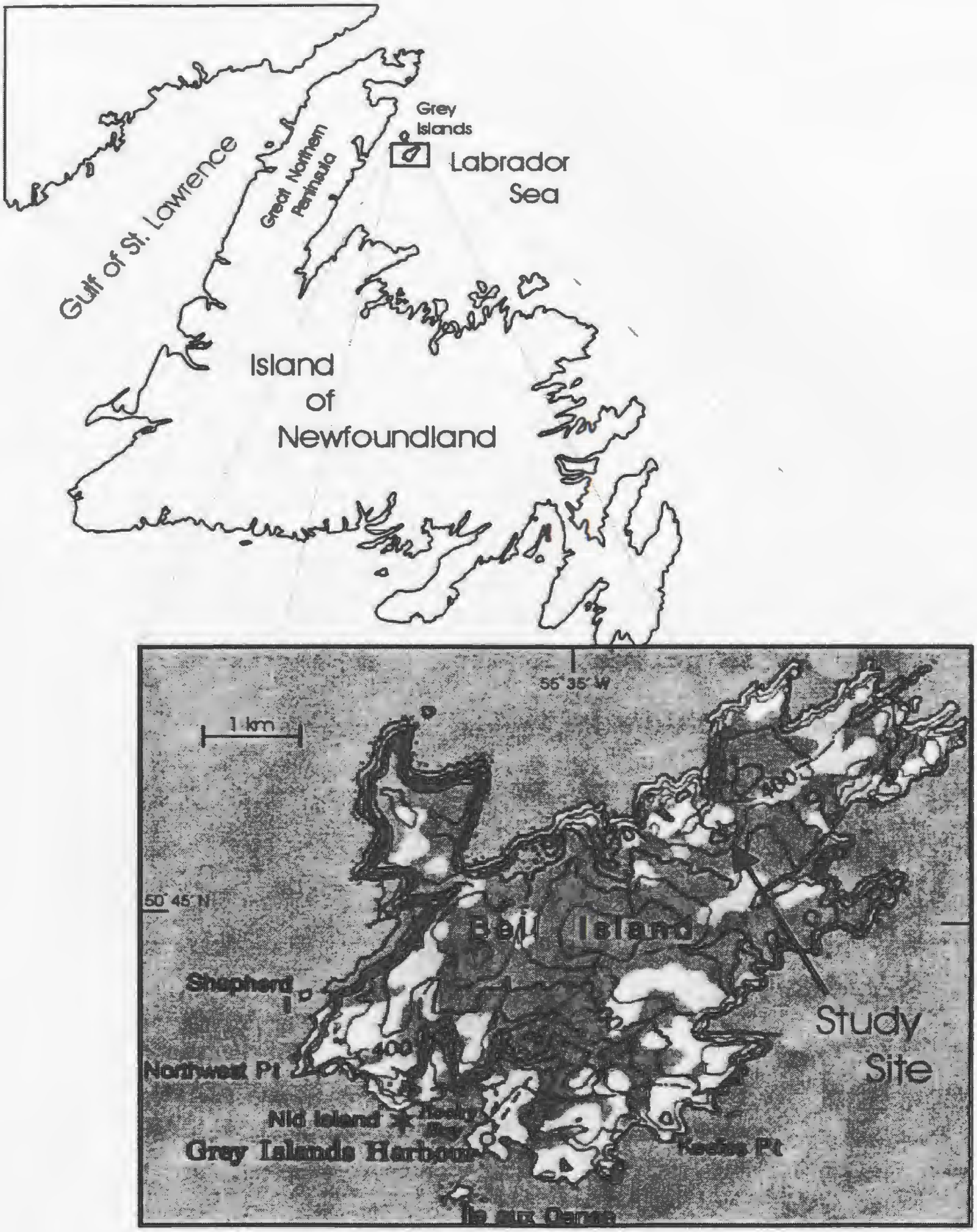

Figure 1.1: Location of the Grey Islands and the study site in northern Newfoundland.
(drafted by Shane Greene, Memorial University, 2001)

1.1 Thesis Structure

As a background to the Grey Islands study, the remainder of Chapter 1 provides a discussion of Late Wisconsinan ice extent in Newfoundland and, more specifically, on the Northern Peninsula. Reconstructions of late Wisconsinan ice extent and changes in relative sea level are also outlined, followed by a summary of the postglacial vegetation and climate in the northwest North Atlantic region.

Chapter 2 outlines the methods of core retrieval, laboratory procedures, and methods of pollen analysis. The Northern Peninsula ecoregion and its glacial history, as well as the physiography, climate, and vegetation of the Grey Islands are discussed in Chapter 3, followed by a more detailed examination of the characteristics of the study site. A description of the pollen data retrieved from the core is given in a summary of identified pollen zones in Chapter 4.

These data provide the basis for a reconstruction of the Grey Islands' postglacial vegetation as described in Chapter 5. The regional context and climatic implications of the pollen record are discussed in Chapter 6.

1.2 Literature Review

The purpose of this section is to describe the late- and postglacial environmental history of the study region. An outline of Late Wisconsinan ice extent in Newfoundland is followed by a discussion of deglaciation and relative sea-level history. Next is a summary of the late- and postglacial vegetation of Newfoundland and southeastern Labrador, followed by a reconstruction of their respective palaeoclimates.

1.2.1 Late Wisconsin Ice Extent, Deglaciation, and Sea-level Changes

The extent and origin of the last glaciation in the northwest North Atlantic region has been a topic of debate among researchers (Dyke and Prest, 1987). A "maximum model", as described by Mayewski *et al.* (1981), depicts a large regional ice mass which was contiguous with, if not an integral part of, the Laurentide Ice Sheet, covering the region and flowing uniformly to the continental margin. However, the prevailing and perhaps more generally accepted model is one of a multicentred local maritime ice complex with localised ice dispersal centres (Fig. 1.2; Dyke and Prest, 1987; Grant, 1977). Some coastal and continental shelf areas probably remained ice-free during the last glacial maximum, and high summits may have survived as nunataks (Grant, 1994; Ritchie, 1987). These would have served as important plant refugia (Ritchie, 1987).

Grant (1989) summarised the Quaternary history of Newfoundland as one of Wisconsinan glaciation independent of the Laurentide Ice sheet, with radial flow from a Newfoundland centred ice cap. He indicates that evidence of earlier advances are found on mountain summits, and that three main glacial phases are identified by "three till terrains with different geomorphic maturity which are in mutual contact" (Grant, 1994). The upper zones lack glacial attributes, exhibiting a mature character which Grant (1994) considers to have been extraglacial during the late Wisconsinan glaciation. He cites this as evidence for ice advance from local centres to reach "progressively lower and less extended limits" (Grant, 1989). Mayewski *et al.* (1981), however, suggest that these geomorphic variations are the result of differing thermal regimes beneath the ice. They

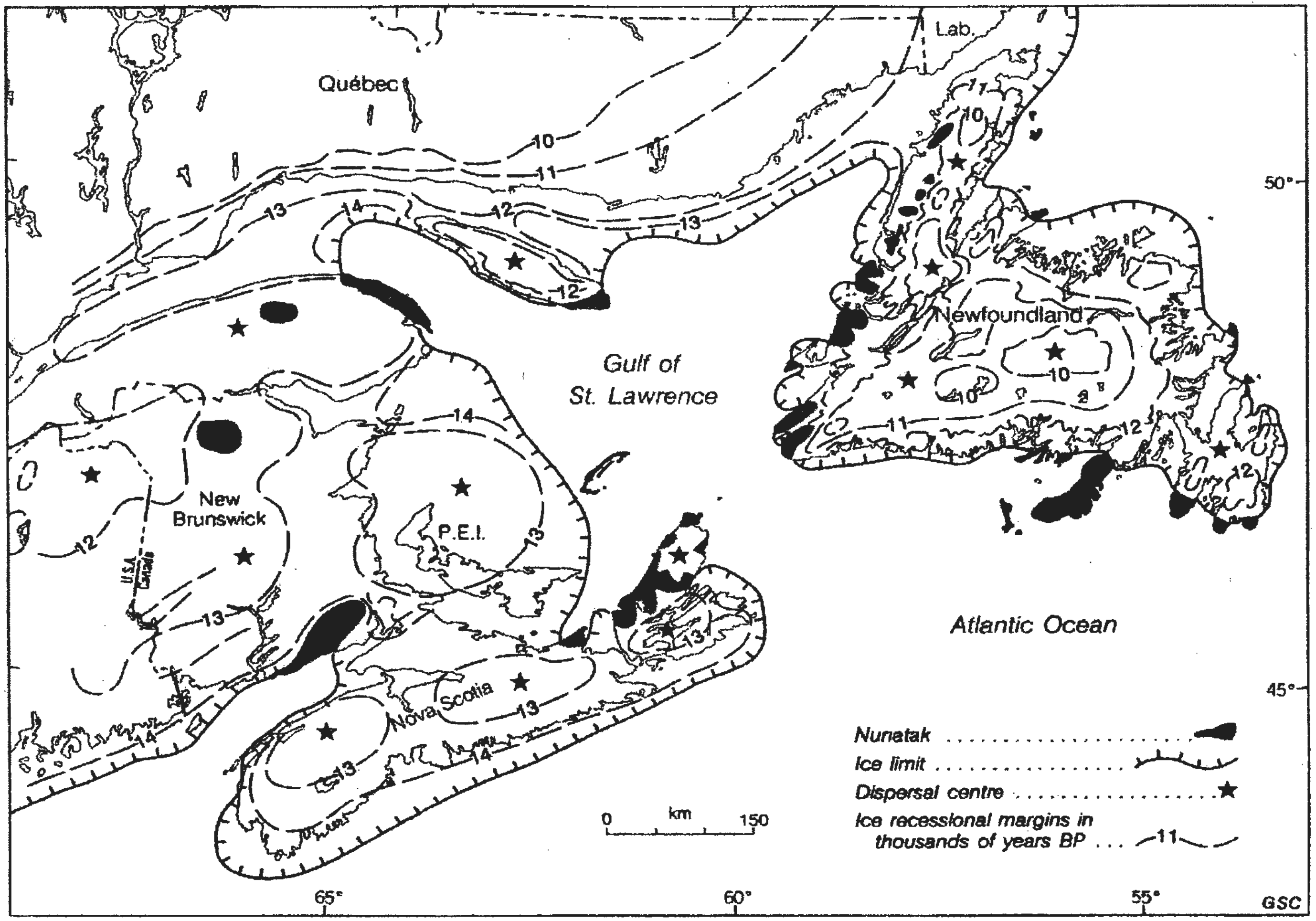

Figure 1.2: Hypothetical limit of Late Wisconsinan glaciation in the Atlantic Provinces. (from Grant, 1987)

believe that the smooth summits were glaciated and weathered at an earlier time, and that they were protected from erosion during the last glaciation by cold-based ice.

Grant, however, discusses maximum versus minimum models of ice extent in his 1989 review and concludes that based on the sea-level studies of Quinlan and Beaumont (1981, 1982), "the glacial limits drawn on the basis of geological evidence are corroborated by theoretical models which link observed sea-level change to isostatic crustal rebound" (Grant, 1989).

According to Grant (1992, 1994), at the time of the last glacial maximum the main flow of ice on the Northern Peninsula emanated from the Long Range Mountains dispersal centre, with additional inputs from the Baie Verte Uplands to the southeast. Ice margins generally followed the coast, and drawdown into permanent calving bays is suggested by ice flow trends. After the ice caps had retreated inland of marine limit they stabilized for a time, and in two places readvanced: the Baie Verte ice readvanced into the sea after 12,500 BP[1], as did the northern part of the Long Range ice cap between 11,000 and 10,000 BP (commonly referred to as the Ten Mile Lake readvance), probably in response to the Younger Dryas cooling event (Mott *et al.*, 1986).

More recent work by Josenhans and Lehman (1999) and Dyke *et al.* (2001) suggest a more extensive last ice limit offshore, with ice retreat to the present coast between 14,000 and 11,500 BP. Ice may have advanced in deepening water on the outer continental shelf even while it was retreating elsewhere in Newfoundland (Dyke *et al.*, 2001).

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[1] BP = Radiocarbon years before present

Sea levels fluctuate in response to the growth and decay of ice sheets due to changes in ocean volume (glacio-eustasy) and vertical adjustments of the Earth's crust (glacio-isostasy). In the case of the island of Newfoundland, these crustal adjustments were complicated by the overlapping influences of a continental ice sheet and local ice caps (Grant, 1989; Liverman, 1994). Grant (1992) provides a summary of sea-level changes around eastern Canada in the form of shoreline displacement curves (Fig. 1.3).

Since deglaciation, sea-level change has varied significantly around the island of Newfoundland (Fig. 1.4). Numerical models of crustal rebound predict three types of relative sea-level history for the island (Brookes *et al.*, 1985; Grant, 1994; Liverman, 1994; Quinlan and Beaumont, 1981; Shaw and Forbes, 1990): there has been continuous sea-level fall in the northwest (type A). Most of the island has experienced a long period of sea-level fall followed by a gradual rise to the present (type B). Southeastern Newfoundland has experienced sea-level fluctuations entirely below present (type C).

The study region falls into a type A sea-level history, as documented by Grant (1994; Fig. 1.5). Immediately following ice retreat, the sea inundated the glacio-isostatically depressed coastal lowlands to reach marine limit (up to 140 m above present sea level). Glacial unloading and crustal uplift caused rapid emergence of the coast, which decelerated during the postglacial period. For example, the northern half the Northern Peninsula (including the Grey Islands) experienced a continuous fall in sea level, rapid at first and with a possible stillstand at approximately 10,000-11,000 BP, during the Ten Mile Lake readvance, followed by a more gradual drop in sea level to its present position.

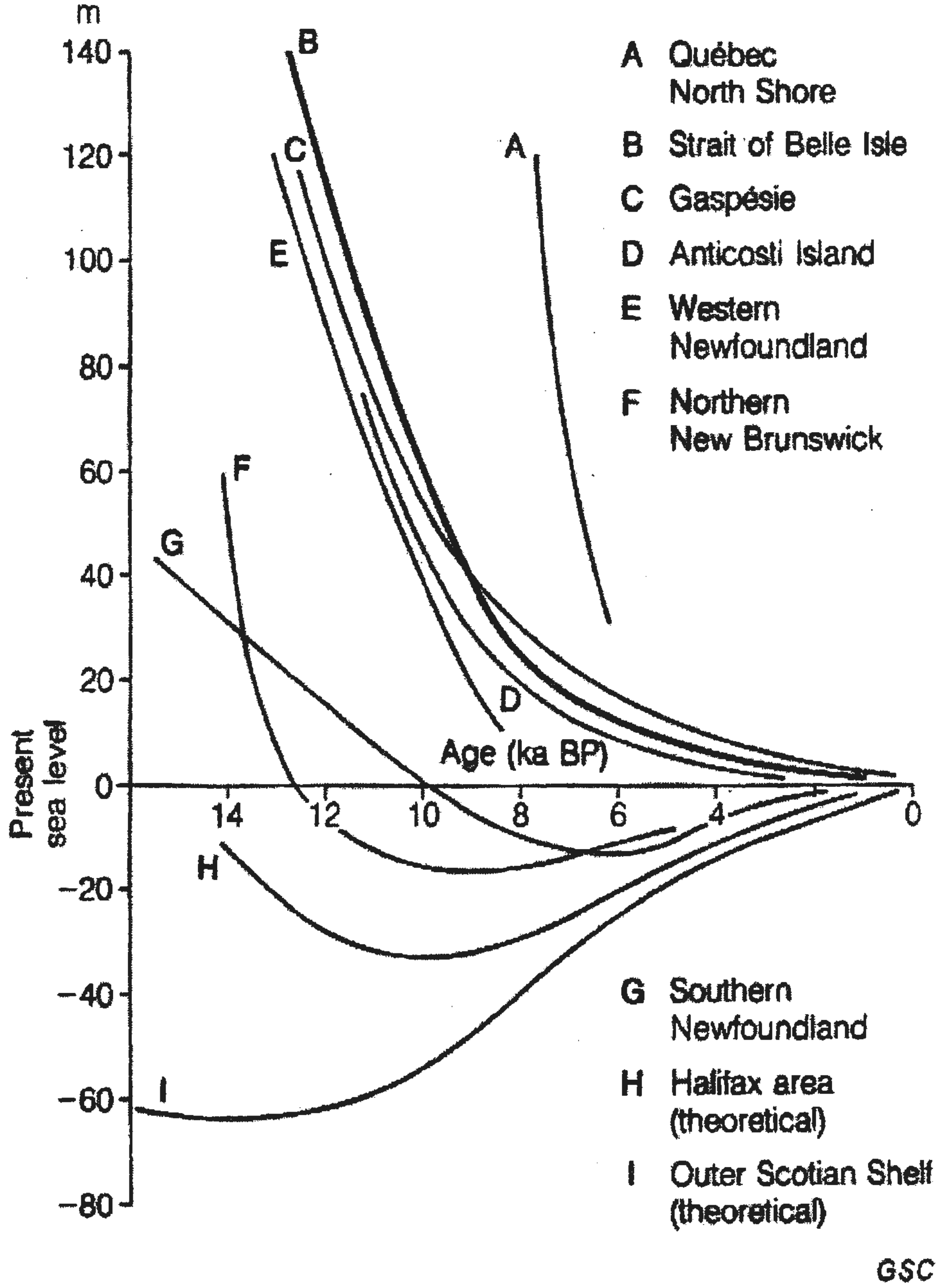

Figure 1.3: Regional postglacial sea-level history.
(from Grant, 1989)

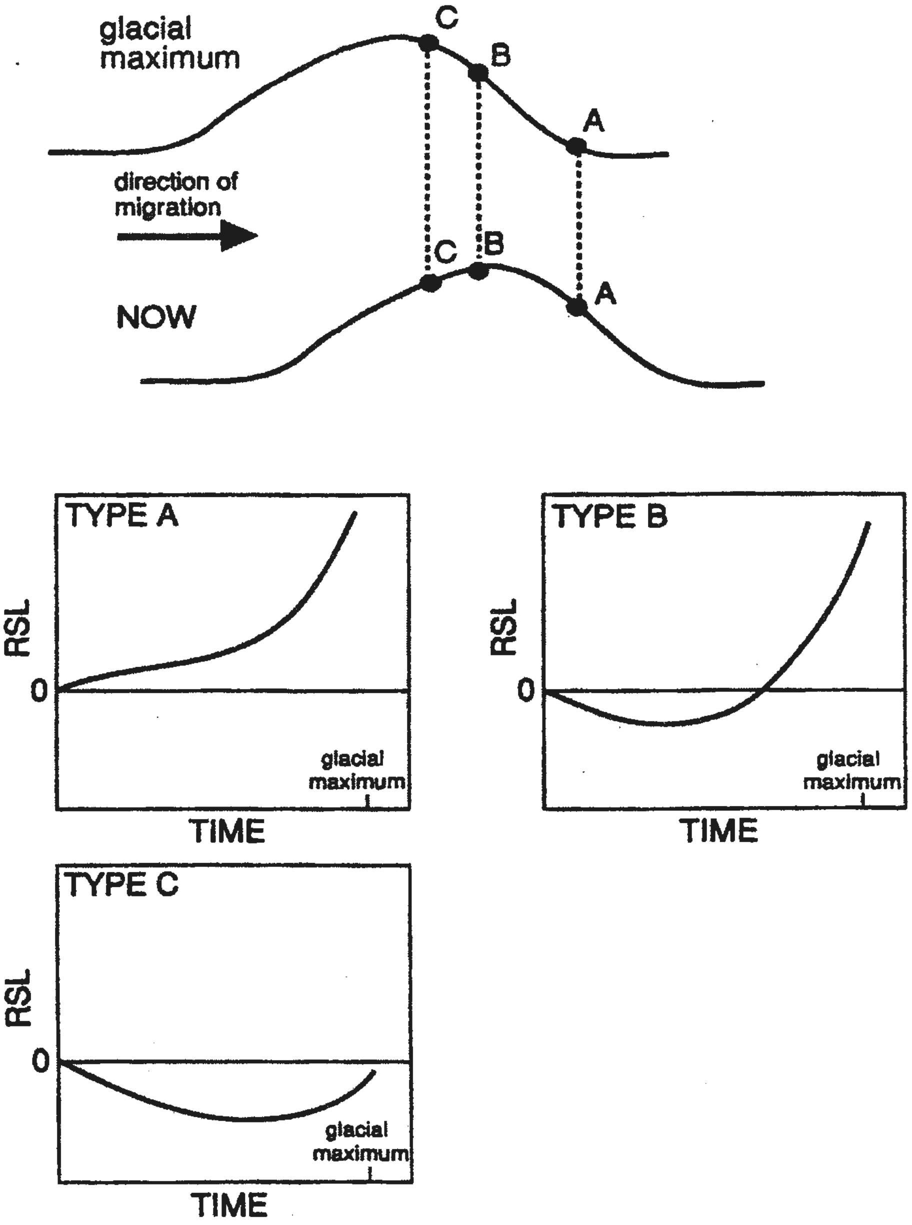

Figure 1.4: Types of sea level curves for Newfoundland. The Grey Islands have a type A history.
(modified from Liverman, 1994)

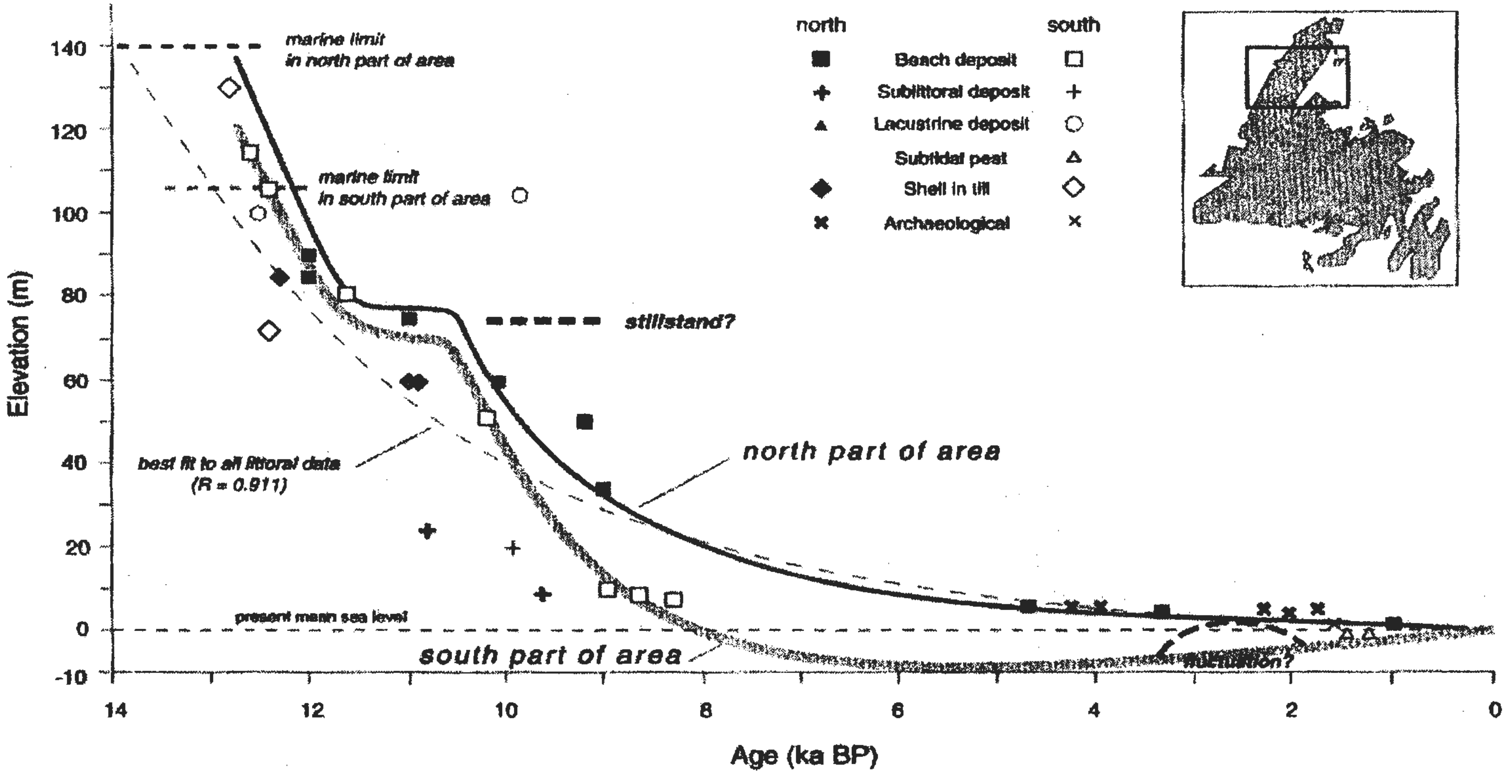

Figure 1.5: This type A curve represents the sea-level history of the north part of the Northern Peninsula, including the Grey Islands. The still stand between 10,500 and 11,500 BP is attributed to reloading of the crust during the Ten Mile Lake readvance.
(modified from Grant, 1994)

1.2.2 Postglacial Vegetation

1.2.2.1 Newfoundland

Anderson and Macpherson (1994) and Macpherson (1995) described the late-glacial vegetation of the island of Newfoundland. Following deglaciation, a shrub-dominated tundra was established in the south and southwest, while a more sparse herb and low-shrub tundra was present in the northeast. A relatively high percentage of *Pinus* pollen at some sites, which must have been transported from distant sources, reinforces the idea of a sparsely vegetated tundra assemblage. Between 11,000 and 10,000 BP, a climatic reversal caused shrub-dominated assemblages to be replaced by herbs. With the end of this reversal and a return to postglacial warming, the herb-dwarf shrub tundra was replaced by shrub-birch heath communities.

After 10,000 BP, poplar and possibly tree birch invaded the shrub-birch heath, followed closely by spruce, the first conifer to arrive on the island. Spruce was present in the southwest of the island by 10,000 BP, in central regions by 9600 BP, but did not arrive in the southeast until 8500 BP. Balsam fir expanded and became established within a few centuries of the spruce invasion. This is interpreted as the beginning of a spruce-poplar-balsam fir forest. A climatic reversal between 9700 and 8500 BP may have initiated re-expansion of the shrub birch tundra at the expense of this forest, especially at higher elevations.

The major elements of Newfoundland's contemporary vegetation were present throughout most of the island by approximately 8000 BP, though tree birch expansion was delayed by as much as 500 years at upland and northern sites. During the 6500-4000

BP interval, pine expanded to its modern limits while black ash may have extended its range beyond that of today. This was also a period of increased fire importance in the central and eastern regions. There was little change between 4000 and 2500 BP. The period following 2500 BP is marked by a decrease in lacustrine organic productivity, a decline in pollen influx and sedimentation rates, and an increase in the rate of peat accumulation (Davis, 1984; Macpherson, 1981).

1.2.2.2 Southeast Labrador

Following deglaciation at approximately 12,000 BP at near-coastal sites and 10,000 BP further inland, the vegetation of southeast Labrador began as an open tundra dominated by sedges, grasses and other herbs. Dwarf willow was the dominant shrub. Dwarf birch and alder were present in very small numbers. Open tundra vegetation persisted, depending upon latitude and proximity to the retreating ice, from approximately 10,500 to 9000 BP (Engstrom and Hansen, 1985; Jordan, 1975; Lamb, 1980; Levac and de Vernal, 1997; Scott *et al.*, 1984; Vilks and Mudie, 1983).

A shrub tundra vegetation dominated by birch and alder, and with a decreasing proportion of willow, was present for the next millennium (Engstrom and Hansen, 1985; Jordan, 1975; Lamb, 1980; Levac and de Vernal, 1997). This assemblage was comparable to the first postglacial communities in Newfoundland, though delayed approximately 3000 years by the presence of the retreating Laurentide Ice Sheet. Beginning 2000 years later than on the island of Newfoundland, from 8000 to 6000 BP, conifers invaded to form what Lamb (1980) described as "park-tundra". Shrubs declined, though were still represented, and white spruce invaded in large number, followed 500 years later by balsam fir (Engstrom and Hansen, 1985; Jordan, 1975; Levac and de Vernal, 1997). A closed-crown fir forest dominated the interior of southeastern Labrador between 7500 and 6000 BP (Engstrom and Hansen, 1985).

Black spruce eventually out-competed white spruce and fir in the forest, probably due to its competitive advantage on recently disturbed sites and its ability to tolerate the increasingly acidic soils (Engstrom and Hansen, 1985; Lamb, 1980). The last 6000 years have been marked by a stable closed crown forest vegetation dominated by black spruce (Engstrom and Hansen, 1985; Jordan, 1975), though a climatic deterioration, as noted in Newfoundland during this time period, may be indicated by a decrease in spruce percentages and a slight increase in alder between 4000 and 2000 BP (Engstrom and Hansen, 1985; Lamb, 1980; Vilks and Mudie, 1983).

1.2.2.3 Northern Peninsula

Three sites on the Northern Peninsula, Stove Pond, Bass Pond, and Saddle Hill Pond, may provide insight into the Grey Islands record (Fig.1.6). The arrival of conifers at these sites was delayed until approximately 7400 BP, and high shrub birch representation persisted longer than at most island sites (Macpherson, 1995, 1997). An even later arrival of conifers (~6000 BP) may be recorded at Saddle Hill Pond, the northernmost site, emphasizing the Peninsula's latitudinal climatic gradient (Bell *et al.*, in press). At Stove Pond, increased fire frequency during the 8000-6500 BP interval may have brought about the expansion of tree birch at the expense of conifers and heathland plants. Reduced fire activity was noted on the Northern Peninsula from 4500-4000 BP. A 3500-2500 BP onset of paludification and cooling are noted at Stove Pond by increases

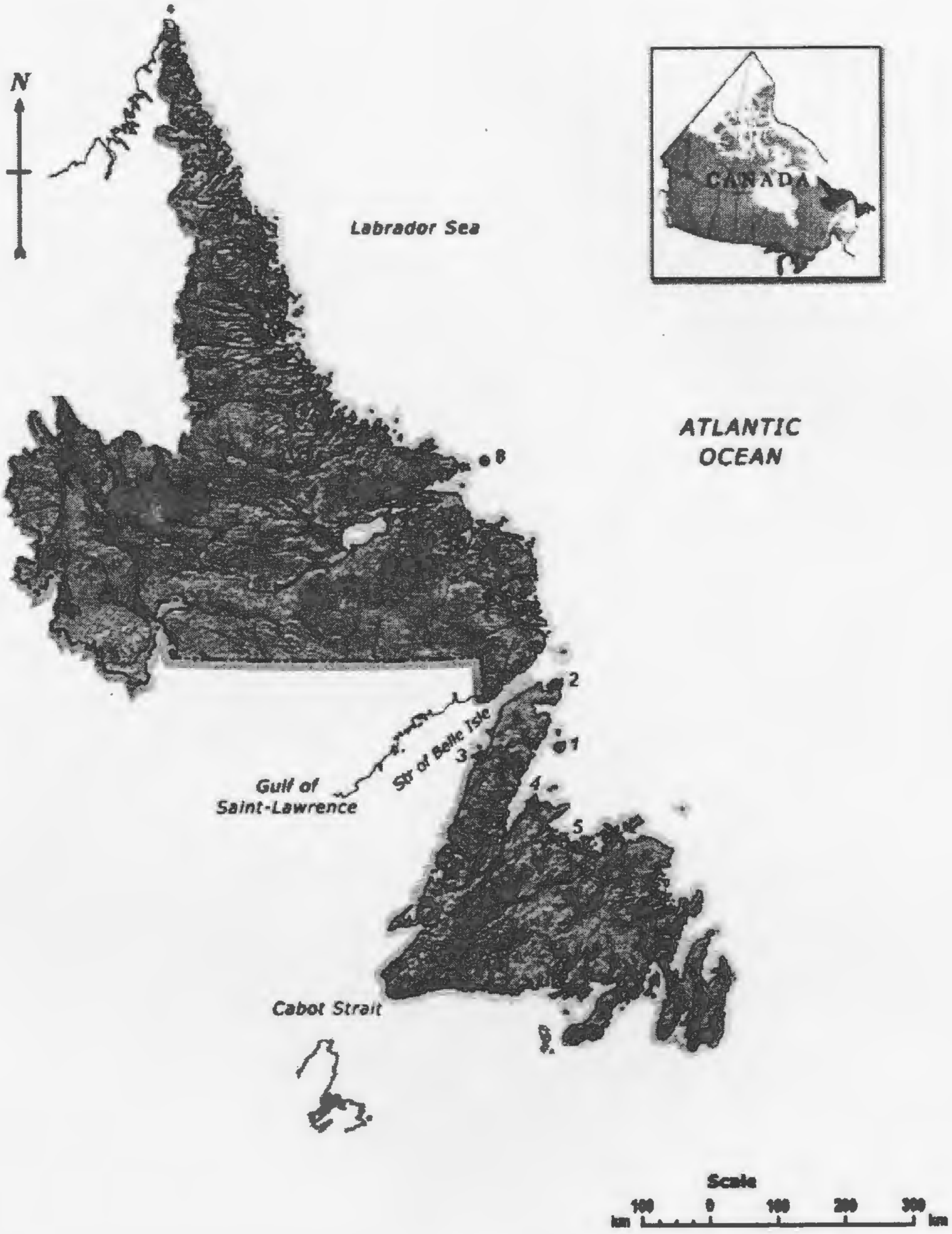

Figure 1.6: Location of fossil pollen sites referenced in text.

1. Grey Islands, 2. Saddle Hill Pond, 3. Stove Pond, 4. Compass Pond (Baie Verte Pen.), 5. Leading Tickles (North Shore), 6. Southeastern Labrador, 7. Lake Melville, 8. Cartwright Saddle

in herbs and sphagnum, as well as by spruce increase at the expense of birch (Macpherson, 1995).

Palaeoenvironmental investigations at the L'Anse aux Meadows Norse site have focused on a peat record of the last 3000 years, bracketing periods of native and Norse settlement. There have been no remarkable changes in the vegetation of the area over the last 2000 years (Bell *et al.*, in press; Mott, 1975b), and the plant communities of 1000 BP were very similar to modern vegetation (Kuc, 1975). Davis *et al.* (1988) suggest that peat growth began at 2500 years BP, coinciding with climatic deterioration noted at other island sites, and that paludification may have been magnified by Norse deforestation 1000 years BP.

1.2.2.4 Baie Verte Peninsula

Dyer (1986) investigated the late-glacial vegetation of Compass Pond, on the Baie Verte Peninsula, 90 km to the southwest (Fig. 1.6). The arrival of conifers at approximately 9500 BP and establishment of closed crown boreal forest by 6700 BP was earlier than on the Northern Peninsula. Between 6000 and 3000 BP there was a decrease in shrub birch and an expansion of black ash onto the Peninsula, north of its present range. An increase in pine was also noted just to the south. Coincident with the deterioration noted at other island sites, black ash was no longer present on the peninsula after 3000 BP and shrub birch increased, followed at 2000 BP by a decrease in influx, and an increase in both shrubs and fir.

1.2.3 Late- and Postglacial Climate of the northwest North Atlantic

1.2.3.1 Newfoundland

A late-glacial warming trend on the island of Newfoundland was interrupted by two documented cooling episodes (Anderson and Macpherson, 1994). A cooling shift began at or around 11,200 BP, evidenced only by a decline in organic carbon at southern sites. At approximately 11,000 BP, corresponding closely to the Younger Dryas climatic reversal, a major cooling event is indicated by an increase in herbs at the expense of shrubs, along with changes in sedimentation and organic content in lake records (Anderson and Macpherson, 1994). This cooling also correlates with the first eastward discharge of glacial Lake Agassiz into the Gulf of St. Lawrence (Anderson and Lewis, 1992) and a recession of the Laurentide Ice Sheet at its Labrador margin, supplying icebergs and cold meltwater to the Labrador Current (Miller and Kaufman, 1990). A second cooling event occurred at approximately 9500 BP, corresponding with another eastward discharge from glacial Lake Agassiz (Anderson and Lewis, 1992). This phase was characterised by the resurgence of shrub birch and the retreat of spruce in the west and southwest of the island. It was marked in the east and southeast by the persistence of shrub tundra (Anderson and Macpherson, 1994).

By 8500 BP Macpherson (1995) suggests a considerable rise in temperatures and increase in the duration of the growing season, based on a rapid expansion of the boreal tree taxa. Black ash arrived in the southwest at 7000 BP as tree birch was expanding its range, indicating increasing summer warmth and a growing season at least as warm and as long as today's. Pine was also expanding its range in the southwest at this time. In central Newfoundland charcoal concentrations were elevated between 8500 and 7000 BP. This may be the result of warmer, drier summers, or may be more closely associated with the presence of pine, known to contribute significantly to the combustibility of the forest. This is demonstrated during the 6500-4000 BP interval, the time of maximum fire importance in central Newfoundland and of greater importance in eastern regions. There is no evidence to suggest reduced moisture during this period, leading Macpherson (1995) to attribute the increased fire frequency to the presence of pine.

The hypsithermal warm interval may be evident in the 6500-4000 BP record of Newfoundland. The Avalon Peninsula registers an increase in ocean temperatures by a rapid decrease in shrub birch and corresponding increase in tree pollen at 6000 BP. This pattern continues, though more gradually, through 4500 BP (Macpherson, 1995). An upland Avalon Peninsula site reached maximum arboreal pollen percentages, pollen influx, and rate of sediment accumulation at 5300 BP (Macpherson, 1982). Also during this interval, black ash extends its northeastern range beyond the modern limit, suggesting a lengthening of the growing season. Balsam fir values are elevated at some sites, possibly as the result of a rise in winter temperatures. This is also a period of greater moisture as evidenced by island-wide increases in *Sphagnum* and, in the north central regions, increases in the values of both *Abies* and *Pinus* (Macpherson, 1995).

After 4000 BP, the island experienced a gradual climatic deterioration. There was a decrease in summer warmth, length of the growing season, and fire frequency (Macpherson, 1995). Rates of organic sedimentation in lakes, indicating declining lacustrine productivity, were significantly reduced throughout the province (Macpherson, 1981). Relative moisture values tended to be higher, resulting in widespread paludification. Increase in *Sphagnum* representation and reduction in forest cover, as inferred from marked reductions in pollen influx to lake sediments, was most marked after 2500 BP (Davis, 1984).

Post-hypsithermal terrestrial cooling was driven by a cooling of the surrounding ocean. Near-coastal sites register a decline in pine or tree birch 500 years before the trend is observed at interior locations. During most of the Holocene, the warmer Outer Labrador Current was dominant near Newfoundland, but since 2500 BP, the Inner Labrador Current has imposed colder bottom water temperatures than at any time since deglaciation, resulting in a climatic deterioration (Macpherson, 1995; Scott *et al.*, 1984).

1.2.3.2 Southeast Labrador

Lamb (1980) interprets the postglacial climatic record of Labrador to be one of continuous warming to a 4000 BP maximum. Levac and de Vernal (1997), through a higher resolution marine core analysis of pollen and dinoflagellate cyst assemblages, instead observe a very cold Arctic environment in southeastern Labrador until 8000 BP. Between 8000 and 7000 BP, as marked by the appearance of balsam fir and a rise in percentage alder, there is slight terrestrial warming, though the sea-surface remained cold. Dramatic temperature increases, both on land and at sea, are recorded after 7000 BP, with full interglacial conditions achieved at 6000 BP. These events are coincident with the postglacial warming trends in Newfoundland, though a true hypsithermal warm interval, as noted around 6000 BP at island sites, is not evident in the records of southeast Labrador.

A decline in pollen influx after 2000 BP is interpreted by Lamb (1980) as a decline in the productivity and density of forest vegetation. Engstrom and Hansen (1984) note an opening in the forest cover with the reappearance of Ericaceae and forb pollen at 2500 BP, as well as a change in the organic component of soil inputs to their studied lake. As on the island of Newfoundland during this time period, these signals are interpreted as a climatic shift to more severe conditions. Jordan (1975) suggests that the influence of a colder Labrador Current, with its associated ice pack, may have been the driving influence for Labrador's post-hypsithermal climatic deterioration.

1.2.3.3 Labrador Sea

Dyke *et al.* (1996) mapped palaeofaunistic zones of dated mollusc assemblages in the northwest North Atlantic over the last 18,000 years. Shallow-water mollusc distributions are controlled by the temperature, salinity, and sea-ice duration in surface waters. Species were divided into classes according to their water temperature requirements: for example, "arctic" species require and are able to survive the coldest environments, whereas "boreal" species need a more intermediate temperature. Temperatures <4°C exclude most boreal species.

The ocean off western Newfoundland was dominated by arctic mollusc species until 8500 BP, after which boreal species became established, although they could not expand farther northward because of the cold Labrador Current. At 8000 BP, northward expansion of boreal taxa was recorded in St. Anthony, on the northern tip of the Northern

Peninsula, Newfoundland. Dyke *et al.* (1996) suggested that this expansion reflects a decrease in the cooling influence of the Labrador Current, and may register the climatic optimum. The waters around Labrador hosted arctic assemblages until 9000 BP. From 9000 to 4000 BP a mixture of arctic and boreal species thrived, after which time boreal species became dominant to the present.

Dinoflagellate cyst assemblages in the Labrador Sea have also been used as proxy indicators of climatic change. The ecology of dinoflagellates is controlled by sea surface conditions, especially temperature, salinity, and phytoplankton productivity (Rochon and de Vernal, 1994). Changes in these variables will be visible in dinoflagellate cyst assemblages and concentration (Levac and de Vernal, 1997). Prior to 11,000 BP, the Labrador Sea was dominated by low-salinity arctic assemblages (de Vernal and Hillaire-Marcel, 1987, 2000). An increase in concentration and diversity of dinocysts is noted between 11,000 and 4000 BP, suggesting high phytoplankton productivity and subarctic surface water conditions (Rochon and de Vernal, 1994). Low-salinity species remain dominant, however, signifying the influence of a Labrador Current which continued to transport large amounts of meltwater (de Vernal and Hillaire-Marcel, 1987). Gajewski *et al.* (2000) look more closely at the dinocyst assemblages between 8000 and 4000 BP, and observe species that they interpret as being indicative of a "weakening cold Inner Labrador Current and its replacement by warmer, more saline Outer Labrador Current water". After 4000 BP assemblages are similar to present, suggesting the establishment of modern sea surface conditions (Levac and de Vernal, 1997).

Studies of calcerous nannofossils (Rahman and de Vernal, 1994) show that the southern Labrador Sea was covered by warm surface waters from the North Atlantic Current between 10,700 and 9000 BP. The Labrador Current was either weak or absent until 9000 BP and became strong by 8400 BP. In their studies of foraminifera, Hillaire-Marcel *et al.* (2001) suggest that the Labrador Current did not attain full intensity until 7000 BP.

Barber *et al.* (1999) observe a dramatic cooling event between 8400 and 8000 BP at selected sites around the North Atlantic. The pattern of cooling at both marine and terrestrial sites suggests that heat transfer from the ocean to the atmosphere was reduced. They hypothesize that a large freshwater influx through Hudson Strait, resulting from the final drainage outburst of glacial lakes Agassiz and Ojibway, modified thermohaline circulation in the North Atlantic.

1.4 Purpose of the Present Study

1.4.1 Objectives

I. The primary objective of this study was to investigate the Late Quaternary vegetation succession of the Grey Islands, Newfoundland. This involved the study of changes in pollen composition, and thus vegetation over time, beginning with postglacial colonization and continuing through to the modern assemblage. This study fills a data gap in the postglacial vegetation history of northwest Newfoundland.

II. Additional objectives were:

Vegetation:

1. To place the Grey Islands within the regional record of postglacial vegetation in Newfoundland, and especially to compare with the established Northern Peninsula record.
2. To determine the timing of the arrival and establishment of the main arboreal species, and to examine to what extent the site was influenced by its extreme setting and coastal location. This is accomplished through the examination of pollen concentration values and their associated radiocarbon dates.

Climate:

3. To interpret, through changes in postglacial vegetation, the sequence of Late Quaternary climate change on the Grey Islands.

Ocean temperature

4. To analyse the postglacial vegetation record for evidence of thermal shifts in the Labrador Current which may have driven terrestrial warming and cooling events (Jordan, 1975; Levac and de Vernal, 1997; Macpherson, 1995; Scott *et al.*, 1984).
5. To determine whether the Grey Islands were influenced more by changes in the surrounding ocean than by the terrestrial climate.

CHAPTER 2 METHODOLOGY

2.1 Field Work and Site Selection

My involvement and responsibilities in this project began with the counting of the pollen. I was not present for the July 1987 field work and subsequent laboratory analyses. The field work was carried out by J. Macpherson, P. Renouf, T. Bell, and T. Sears. Sediment processing and loss-on-ignition analyses were undertaken by R. Rowsell. The Grey Islands were initially chosen as an area of palaeoecological interest by virtue of their potential location beyond the Late Wisconsinan glacial limit. According to Grant (1972, 1994), the last glaciation did not inundate the islands. A lake on the Grey Islands could, therefore, potentially provide evidence of the Younger Dryas cooling event that occurred between 12,800 and 11,500 BP. However, with a basal date of only 9870 BP, chronological and sedimentological evidence of the Younger Dryas was not found. No further investigations were undertaken and the core was put into storage.

2.1.1 Coring

The largest lake on Bell Island (50°46.08'N, 55°31'W) was selected as the sampling site because it was the only lake large enough to accommodate the landing of a float plane. Belvy Aviation in Main Brook was chartered as transportation for the July 1987 sampling expedition. Sampling was undertaken in the northern part of the lake in a water depth of 277 cm. The southern part of the lake was not sampled due to a lack of sediment.

The coring operation was performed from an adapted inflatable boat. A wooden platform, through which the corer was lowered, was attached to the sides of the boat. The lake was sampled with a modified Livingstone piston corer which extracted samples 5 cm in diameter and 1 m in length. A single core was retrieved in 8 sections. A second basal increment (700-800 cm) was cored from an adjacent site, but was not used in the pollen analysis.

Because there were insufficient tubes to contain the entire length of the core, some segments were extracted in the field. These segments were placed into clean plastic troughs, tightly covered with plastic wrap and aluminum foil, and carefully labelled. The troughs were transported horizontally. The remaining core segments were extracted in the same manner upon return to the laboratory.

2.1.2 Vegetation Survey

Modern vegetation at and around the site was noted by J. Macpherson at the time of the sampling expedition. A list of the flora and vegetation types, along with their general location (i.e. near the lake, on rocks, etc.), was compiled for the surrounding area (see section 3.7).

2.2 Laboratory Analysis

Immediately upon returning from the field, 5 ml sediment samples were extracted from the core at 5 cm intervals and stored in plastic vials for pollen analysis. Within two months, 1 ml samples were taken from the vials and processed for pollen extraction.

2.2.1 Stratigraphy

The core was systematically examined while samples were taken for processing in the laboratory. General colour, composition, and consistency were described throughout the core from the Tröels-Smith sediment classification and Munsell soil colour charts. Macrofossils and other extraneous material were noted at the depths where they were found.

2.2.2 Radiocarbon Dating

Soon after core retrieval, four bulk organic sediment samples were selected and submitted to the Geological Survey of Canada for conventional radiocarbon dating. More recently, following preliminary pollen analysis, three macrofossil samples were submitted to the IsoTrace Radiocarbon Laboratory at the University of Toronto for dating by accelerator mass spectrometry. In the former method, necessity of a large sample size requires that a bulk sediment sample be submitted, though bioturbation and other factors may result in a sample which is not homogenous. There is also potential for a hard water error in which limestone or other calcerous rocks are included in the sample causing it to appear older. These factors are not a problem in AMS dating, and the results received through the latter method are intended to evaluate the existing conventional dates and to anchor the chronology of the core.

The bulk material for radiocarbon dating was selected as follows: a basal sample (702-712cm) was extracted from the lowest level of clay-gyttja, beneath which lay clay and sandy clay. This sample would determine the date of post-emergence isolation of the lake. A sample was taken from the middle of the core's lower "plateau" of organic carbon content (605-610cm), another was taken where the organic carbon content began a rapid increase (405-410cm), and the fourth was taken at the point of highest organic content (210-215cm). Two additional macrofossils, a twig and a *Picea* needle, were selected from the top of the core (41.5 and 104.5cm), while a third macrofossil near the base (680cm) yielded an insufficient amount of dateable carbon.

The radiocarbon time scale is used in this thesis because most of the dated pollen records from the region use radiocarbon age. The reported radiocarbon dates were calibrated using the University of Washington's online CALIB programme (Stuiver and Reimer, 1993). CALIB makes the conversion from radiocarbon age to calibrated calendar years, and calculates the probability distribution of the sample's true age.

2.2.3 Loss-on-ignition

Loss-on-ignition analysis was performed by R. Rowsell in July and August 1987. Analysis on two samples that had outlying results (15 cm and 195 cm) was repeated in July 1999. Loss-on-ignition results present a record of changes in organic carbon content of the sediment through a core, which in turn provides information about terrestrial biomass productivity and the nutrient status of a lake (Lamb, 1980).

Loss-on-ignition analyses were performed on the Grey Islands core at a sampling interval of 10 cm. The procedure, after the technique outlined by Bengtsson (1979), is as follows:

1. A porcelain crucible was ignited for one hour at 550°C in a Thermolyne 1400 furnace and cooled to room temperature. The *weight of the crucible* (a) was noted.

2. A sediment sample was placed into the crucible and dried overnight at 105°C.
3. The sample was cooled for two hours in a desiccator. The *weight of the crucible + oven-dried sample* (b) was noted. The sample was pulverized in a mortar to ensure its complete ignition in step 4.
4. A lid was placed on the crucible containing the dried sample in order to avoid ash losses. The crucible with sample was placed in a preheated furnace at 550°C for two hours.
5. After cooling, the *weight of the crucible + ignited sample* (c) was noted.

The calculation for loss-on-ignition is as follows:

$$(b-c / b-a) \ X \ 100\%$$

2.2.4 Macrofossils

The Grey Islands core was not systematically analysed for macrofossils.

2.3 Pollen Analytical Methods

2.3.1 Sampling and Processing

R. Rowsell sampled and processed the sediment for pollen extraction in July and August 1987. The core was sampled at 5 cm intervals, though pollen analysis was initially undertaken every 10 cm and increased to 5 cm where higher resolution was required. 1 ml sediment samples were taken for processing. The procedure for pollen extraction followed the standard method outlined in Faegri & Iversen (1989):

1. To deflocculate, remove humic acids, and remove coarse organic debris from the sediment: Add 10% KOH (potassium hydroxide) to 1 ml

sediment samples. Place in a water bath and heat to boiling. Strain the material and rinse down with distilled water.

2. To remove cellulose through acetolysis: Wash the samples first in glacial acetic acid. Acetolyse the material in a mixture of acetic anhydride (CH_3CO_2O) and concentrated sulfuric acid (H_2SO_4). Boil in a water bath for 5 minutes and wash with glacial acetic acid. Give several rinses with distilled water.
3. To stain and dehydrate the material: A few drops of stain is added to the remaining material, followed by tertiary butyl alcohol as the dehydrating agent.
4. To mount on microscope slides: Add silicone oil, a very effective mounting medium.

Samples below 400 cm in the core had a high mineral content, so were processed with hydrofluoric acid.

2.3.2 Absolute Pollen Extraction

In order to calculate absolute pollen frequencies, in addition to percentages, an exotic marker grain was added to the sediment samples prior to processing. A measured volume of a suspension of exotic pollen (*Eucalyptus*) of known concentration was added to the 1 ml samples. Fossil pollen concentration, in which the abundance of any pollen type is independent of all others, is calculated as follows:

$$(\text{Fossil grains}/\text{Exotic grains}) \times \text{added pollen concentration} = \text{Fossil Pollen Concentration (grains/cm}^3)$$

Together with sediment accumulation rates derived from radiocarbon dates, the fossil pollen concentration can be used to determine pollen influx:

Fossil Pollen Concentration x Sedimentation Rate = Pollen Influx (grains/cm^2/yr)

2.3.3 Microscopy

Pollen identification and counting was performed on a Fisher Scientific binocular microscope between October 1999 and December 2000. A total magnification of x400 was used. This was accomplished with a x40 objective and x10 oculars. Grain measurements were made with an ocular micrometer scale where one division was equal to 2.5 µm at a total magnification of x400. Traverses were made at 2 mm intervals across the slide.

2.3.4 Pollen Sum

The pollen sum chosen for this study incorporated tree, shrub, and herb pollen because the general postglacial recolonization of the Grey Islands was of primary interest. The percentage frequency of a taxon (e.g. *Abies*) within the pollen sum (ΣP) is calculated as follows:

$$(\Sigma\, Abies / \Sigma\, \mathrm{P})\ 100 = \%\, Abies$$

In calculating the percentage frequency of any group which was outside of the pollen sum (i.e. spores, aquatics, *Pediastrum*, inderterminable, and unknown), the pollen sum was added to the sum of that group so that it was impossible to attain a value greater than 100%. The calculation, using spores as an example, is as follows:

$$(\Sigma\ \mathrm{Spores} \times 100) / (\Sigma\ \mathrm{Spores} + \Sigma\ \mathrm{P}) = \%\ \mathrm{Spores}$$

Previous studies in Newfoundland (e.g. Macpherson and Anderson, 1985) have demonstrated that a count of 300 grains provides a reasonable pollen sum. This is the sum that was used in the present study. In the lower levels of the core, however, pollen frequency became so low that this count was no longer feasible. Two slides were made for each level in the core, and below 560 cm both slides were counted without reaching the 300 grain requirement. Between 560 and 610 cm, pollen sums averaged 250 grains, and from 620 to 705 cm they averaged only 53 grains per level.

2.3.5 Pollen Diagram Construction

2.3.5.1 Pollen diagram format

The pollen diagram is the traditional graphic method for the display of multiple time series stratigraphic pollen data from a single site (Grimm, 1988). The final pollen counts for this project have been presented separately as pollen percentage, concentration, and influx diagrams. The Tilia computer programme was used to manipulate the data and to produce these diagrams (Grimm, 1992). The same format was used for each of the three diagrams.

The vertical axis of each diagram is defined by depth (cm) in the core below the surface. Next to the vertical axis are radiocarbon dates (in corrected radiocarbon years BP) and their one-sigma standard deviations. The main part of each diagram is divided into physiognomic categories into which individual pollen profiles are placed. These categories are: trees, *Betula*, shrubs, herbs, spores, aquatics, *Pediastrum*, and charcoal fragments. *Betula* is isolated because its pollen is unique in that it may be of either the tree or shrub variety. The differentiation between "tree" and "shrub" pollen is inferred from differences in grain diameter (Dyer, 1986). *Pediastrum* is isolated because it is an alga which provides information about the nutrient status of the lake. The horizontal axis of each profile is either percent, concentration (grains/cm^3), or influx (grains/cm^2/yr) of pollen. Local pollen zones, which are discussed in the next section, are identified to the right of the diagram.

Percentage, concentration, and influx pollen data are represented diagrammatically because each provides complementary information to the other two and to the study as a whole. Percentage data are inherently deceptive because of the constraint that all percentages add to 100%, and therefore all values are dependent upon others in the sum. If one species increases dramatically, it produces an observed decrease in all other species though in reality they may not have decreased at all, and could actually have experienced a small increase. Pollen concentration diagrams are able to provide information on the absolute abundance of individual taxa that is independent of all other taxa (Moore *et al.*, 1991). However, because of differential sedimentation rates through time or sediment focusing, the pollen concentration diagram may also contain inaccuracies (Grimm, 1988). The percentage and concentration diagrams are therefore complemented with pollen influx, which takes into consideration sediment accumulation rates.

2.3.5.2 Pollen zonation

In order to aid the description and interpretation of the pollen sequences, the pollen diagrams have been divided into pollen zones and subzones. These zones are site specific and are therefore referred to as "local zones". Ideally, a pollen assemblage zone should be a biostratigraphic unit that is defined purely upon its pollen content. It should be internally homogeneous and display recognizable pollen characteristics upon which it is distinguished from other zones (Moore *et al.*, 1991). Birks (1980) defines the pollen zone as "a body of sediment with a consistent and homogeneous fossil pollen and spore content that is distinguished from adjacent sediment bodies by differences in the kind and frequencies of its contained fossil pollen and spores". Zones should be named for two or more of the prominent and diagnostic taxa in the affiliated assemblage (Grimm, 1983).

Pollen zone boundaries were located using both visual and statistical analysis. Statistically-based zonation relies solely upon the actual fossil pollen count and may be more reliable than its visual counterpart because there is no human subjectivity involved. Using both visual and numerical methods together produces generally the same result, and anomalies between the two may then be further examined in order to find an explanation (Birks and Birks, 1980).

A numerical zonation procedure was carried out on the pollen data using CONISS, a programme that performs a stratigraphically constrained cluster analysis. Data transformation may be performed on both the raw count and the percentage data, each giving a slightly different result with which to work. The most appropriate zone boundaries were located by comparing and contrasting the two numerical transformations, as well as incorporating a visual judgment. With the CONISS programme, only pollen and spores of non-aquatic taxa are included. Also, in order to be included, a taxon must attain a value of at least 5% of the pollen sum at some level of the profile. Qualifying taxa included: *Abies, Fraxinus, Picea, Pinus, Populus, Quercus,* *Betula* (both shrub and tree), *Coryloid* (grains that could be either *Corylus* or degraded *Myrica*), Ericaceae, *Alnus, Myrica, Salix,* Cyperaceae, Poaceae, *Artemisia,* Polypodiaceae, *Lycopodium,* and *Sphagnum.*

2.3.6 Pollen and Spore Identification

Pollen and spore identification in this study was almost exclusively to the genus level. The morphological similarity of members within a genus impeded identification to the lower taxonomic level. A notable exception to this was the case of *Betula.* Differentiation between the pollen of "tree" and "shrub" birch was based upon differences in grain diameter (Dyer, 1986). Grains which measured less than 20μm were classified as "shrub" birch and those which measured over 25μm were classified as "tree" birch. All grains which fell between the two size designations, and these were in the majority, might have come from either shrub or arboreal sources. This situation results from the presence of birch species whose grain diameters overlap the designated "shrub" and "tree" boundaries, notably *Betula cordifolia* whose grains range from 20 to 34 μm (Dyer, 1986).

Pollen identification was facilitated by reference to a collection of modern samples from the region, as well as the use of several keys. The determination of rare and difficult grains, as well as general identification, was largely undertaken with the following keys: McAndrews *et al.* (1973), Moore *et al.* (1991), and Kapp (1969).

2.4 Approaches to Vegetation Reconstruction

The overall intent of this study is to aid in the reconstruction of past vegetation and climate on and around the Grey Islands, and to insert it into the larger record of

Eastern Canada. But, in order to move from pollen sequences in a sediment profile to past vegetation communities, some objective analyses must be rendered and some inferences made. The primary methods employed in making this transition are discussed below.

The comparative approach is considered by MacDonald (1988) to be "the most powerful technique for reconstructing vegetation history from pollen records". This approach involves the comparison of fossil assemblages with modern samples from known vegetation types in search of a modern analogue. When a match is found, it is assumed that the community of vegetation which created the fossil assemblage is the same as that which produced its modern counterpart. There are, however, many problems inherent to this method. There is not always a modern equivalent to the fossil assemblage, and in Newfoundland, because of a limited number of studies of the modern pollen-vegetation relationships, there may simply be none available (Macpherson, 1982). Also, the vegetation at any time is a function of contemporary climate, site peculiarities, edaphic modifications, previous vegetation, and past climate, the latter four of which are unique to that point in time and may not correspond to the modern situation (Guiot, 1989). Thus, care must be taken in making concrete determinations of the composition of a past vegetation community based upon what seems a perfect modern analogue.

Another method employed in the reconstruction of palaeovegetation is the use of "indicator species", defined by Birks (1979) as "morphologically distinctive pollen and spores of taxa of narrow ecological or sociological amplitudes today that are characteristic or diagnostic of particular present-day plant communities". The success of this approach is obviously dependent upon the assumption that the ecological tolerances of the indicator species have not changed over time. This can be overcome to some extent by using an "indicator group" of species that have similar ecological tolerances and commonly occur together in the modern spectra, the behaviour of which is less likely to vary as significantly as that of only one species.

The abundance of charcoal in the sequence can also provide information about palaeovegetation communities. Large amounts of charcoal, indicating the occurrence of a forest fire, precede a secondary succession event. This will help to explain adjacent changes in the relative abundance of trees, shrubs, and herbs.

This study employs multiple approaches to vegetation reconstruction, including those outlined above, as well as reference to published interpretations of fossil pollen assemblages from Newfoundland and the northwest North Atlantic region as a whole.

CHAPTER 3 REGIONAL SETTING

3.1 Location

The Grey Islands (50°54'N, 55°36'W) are located north of White Bay in the Labrador Sea, and are situated approximately 20 km east of Newfoundland's Great Northern Peninsula (Fig. 1.1). They are comprised of several offshore rocks and shoals along with two large islands, Bell Island and Groais Island. Groais Island, 9.6 km long and 4 km wide, is the smaller of the two. Bell Island, situated approximately 8 km south of Groais Island, is 13.6 km long and 9.6 km wide.

The islands are high (200-300 m rolling uplands), flat, and rocky, and are surrounded by sheer cliffs. The only suitable harbour, Grey Islands Harbour, is situated at the southwestern extremity of Bell Island. Vegetation is somewhat sparse and is dominated by tuckamore (dwarf shrub barrens) with patchy areas of black spruce forest and sphagnum bog (Fig. 3.1).

The Grey Islands have been known to fishermen since the 1500s and became home to a permanent settlement in the late 1800s. The inhabitants, almost all of whom settled on Bell Island, were largely dependent upon the cod fishery and seal hunt. A church and school served the population which, at its height in 1884, consisted of 166 residents (Encyclopaedia of Newfoundland and Labrador, 1967). Between 1961 and 1966 all residents of the islands were resettled.

Figure 3.1: Vegetation surrounding the study site.

3.2 Lake Characteristics and Drainage

The unnamed lake cored for the study (104 m above sea level) is located in northeastern Bell Island. This pond, the largest on the island, measures approximately 208 by 750 m with its longer axis trending northeast (Fig. 3.2). An outlet drains the lake to the northwest and two small streams flow into the lake from the surrounding woodland to the south. The lake's catchment is approximately 3.5 km^2. The core was taken towards the northeastern end of the lake where water depth was 2.77 m and sediment thickness was at least 8 m.

3.3 Geology and Physiography

Bell Island is predominantly underlain by Devonian granite (also referred to as Bell Island Granite, Fig. 3.3), though the western third of the island is composed of metasedimentary carboniferous rocks that have been post-tectonically intruded by the granite (Williams and Smyth, 1983). These carboniferous rocks occur in major northwestward facing anticlinal folds which are a continuation of a larger belt of similarly situated folds found on the Baie Verte Peninsula. They are structurally and lithologically similar to that peninsula's Fleur de Lys Supergroup (Baird, 1965; Kennedy *et al.*, 1973).

The Grey Islands are part of the Uplands of Newfoundland, a subdivision of the Appalachian Physiographic Region, which is a mosaic of highlands, uplands, and lowlands with its northern terminus in Newfoundland (Grant, 1992, 1994). The islands are ringed by sheer cliffs which give way to rolling uplands at 200-300 m. These upland

Figure 3.2: Study site (lake in the middle background).

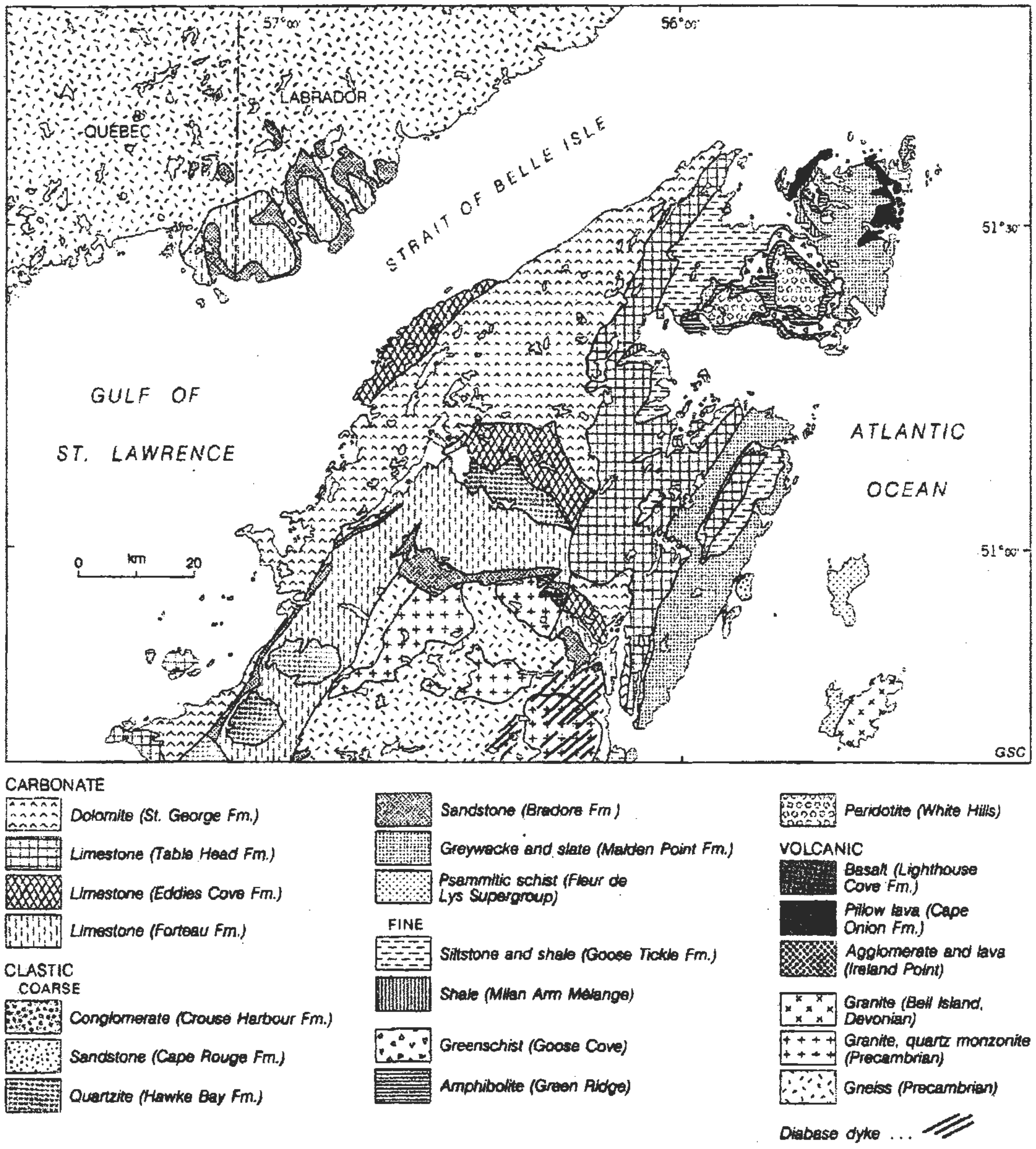

Figure 3.3: Bedrock geology of the study region.
(from Grant, 1992)

may be an extension of the Long Range Peneplain which slopes eastward from about 600 m above sea level on the western edge of the Long Range Mountains (Grant, 1994).

Eight large U-shaped basins, 1-2 km wide, with 200-300 m headwalls, and with floors 20-40 m below sea level, ring the cliffs of Bell Island. At least two of them contain emerged marine sediment. Grant (1992, 1994) speculates that they may be partially submerged cirques formed during an early glaciation and successively cut during the early stages of each major glaciation thereafter.

Bell Island is dominated by exposed bedrock in the north and south and glacial deposits in the interior. The extent of bedrock roughly marks the marine limit on Bell Island because during post-glacial submergence, wave action eroded areas of surficial deposits (Grant, 1994). Bell Island exhibits a mature glacial character which may record earlier glaciations than does most of neighbouring Canada. Above marine limit, the island's surface is composed of till and blockfields with mature slope degradation. The till surface is littered with erratics of Cambro-Ordovician sandstone, dolomite, and gneisses originating from the Northern Peninsula and southern Labrador (Grant, 1992, 1994). Stone stripes and an absence of morainic topography suggest a long period of unglaciated surface smoothing by solifluction (Grant, 1992, 1994).

3.4 Glacial Morphology and History

The Northern Peninsula and surrounding region was inundated by ice from two sources: The Laurentide Ice Sheet and a local Newfoundland ice cap of the Appalachian Glacier Complex. Ice-dispersal centres for the Newfoundland ice cap were the Long Range Mountains and the Baie Verte Uplands. Grant assumes, from the orientation of glacial landforms (Fig. 3.4) and the origin of erratics, that the Grey Islands were affected only by Laurentide ice. A southeastward trending roche moutonnée, which was moulded by ice moving from the northwest, provides evidence of inundation by Laurentide ice. The till surface of the Grey Islands is also littered with erratics of Cambro-Ordovician sandstone and dolomite from the Northern Peninsula, gneisses from either the Long Range Mountains or Labrador, and Shield erratics from the adjacent continent.

According to Grant (1992, 1994), the Quaternary history of the Grey Islands and the surrounding region was shaped by three major glaciations. The first and most extensive glaciation probably occurred in the early Middle Pleistocene. An ice sheet from mainland Canada invaded the northern part of the region, depositing Shield erratics from southern Labrador on the Grey Islands and an ice-contact marine delta (elevation 136 m) at the southern extremity of Bell Island. The ice sheet extended out into the Atlantic at least as far as the eastern end of the Baie Verte Peninsula. The apparent geomorphic maturity of the landscape on Bell Island led Grant (1994) to conclude that this was the last glaciation to inundate the island. The second major glaciation probably occurred in the late Middle Pleistocene, with mainland ice covering Groais Island and regions north, while radial flow from the local Newfoundland Ice Cap affected other parts of the Northern Peninsula. Grant concluded that Bell Island remained ice free at this time. Likewise, during the last major glaciation, the Late Wisconsinan, the Grey Islands remained ice free.

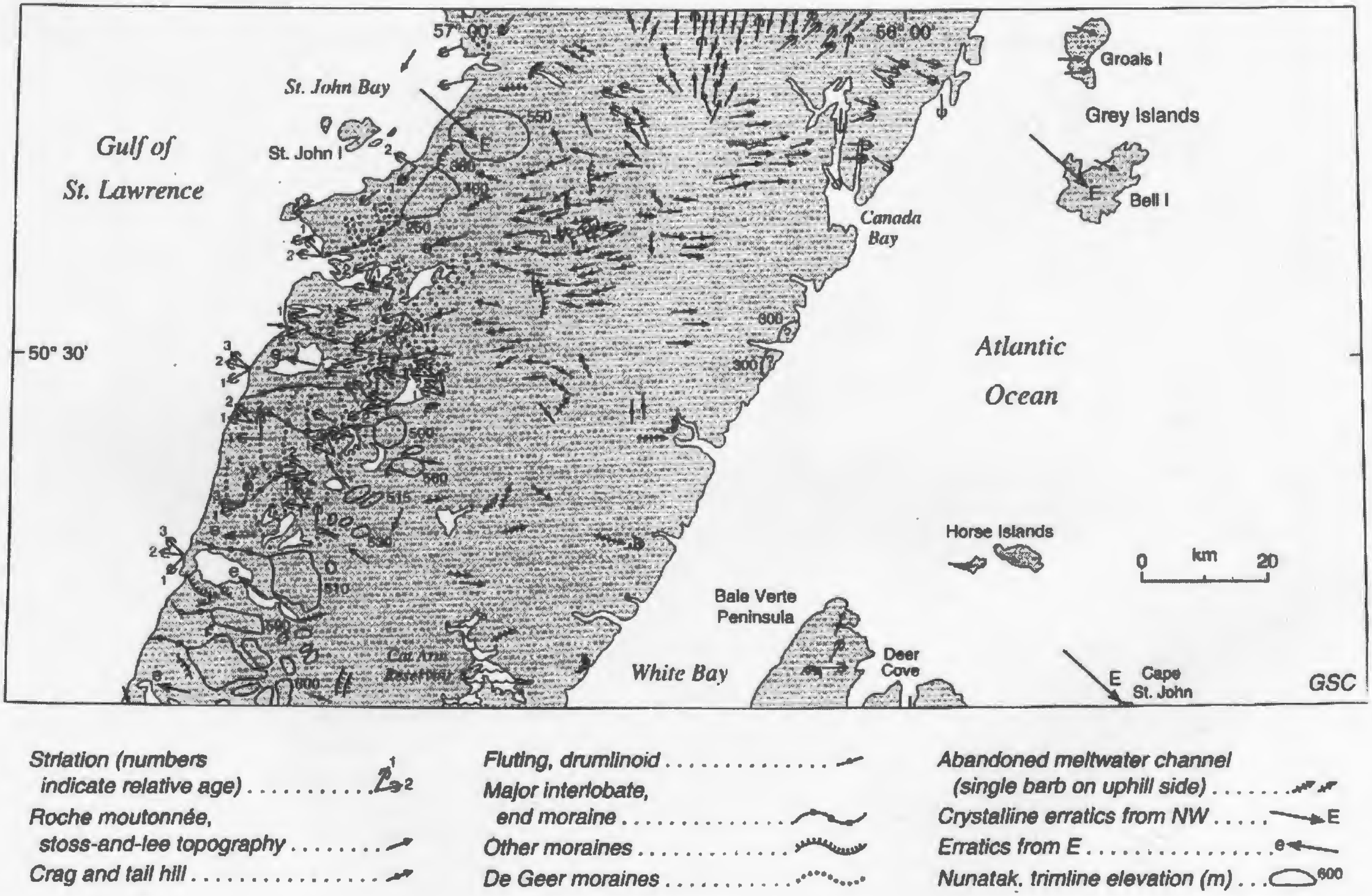

Figure 3.4: Summary of ice-flow indicators.
(from Grant, 1994)

Approximately half of Bell Island was inundated by the sea at the end of the last glaciation due to glacio-isostatic depression associated with the Laurentide and Newfoundland ice masses during the last glaciation and post-glacial period (Grant, 1994) (Fig. 3.5). The Holocene marine limit on Bell Island slopes from 136 m asl in the west to 122 m asl in the east, but remains undated. Postglacial emergence is assumed to mimic the northern half the Northern Peninsula which experienced a rapid drop in sea level until approximately 10,000-11,000, when a short lived stillstand possibly occurred, followed by a more gradual fall in sea level to its present position (Grant, 1994).

3.5 Soils

Roberts (1983) does not specifically address the soils of the Grey Islands, but does describe those of the nearby Long Range Mountains physiographic zone which are summarised here. At high elevations Typic Folisols of the Organic Order along with Orthic and Gleyed Regosols are derived from shattered bedrock. Coarse textured, well drained Orthic Humo-Ferric Podzols, composed of mixed till and colluvium, dominate on steep slopes. Other significant soils include Gleyed and Ortstein Humo-Ferric Podzols with peaty phases.

3.6 Climate

The climate of the Northern Peninsula is abnormally cold for a temperate latitude, the same as Paris and Vancouver. Hare (1952) aptly states that “nowhere else on earth does the arctic verge drive so far south into the middle latitudes”. This is largely attributed to the chilling effect of the nearby Labrador Current (Fig. 3.6). This cold ocean current originates at the eastern end of Hudson Strait and flows south in two

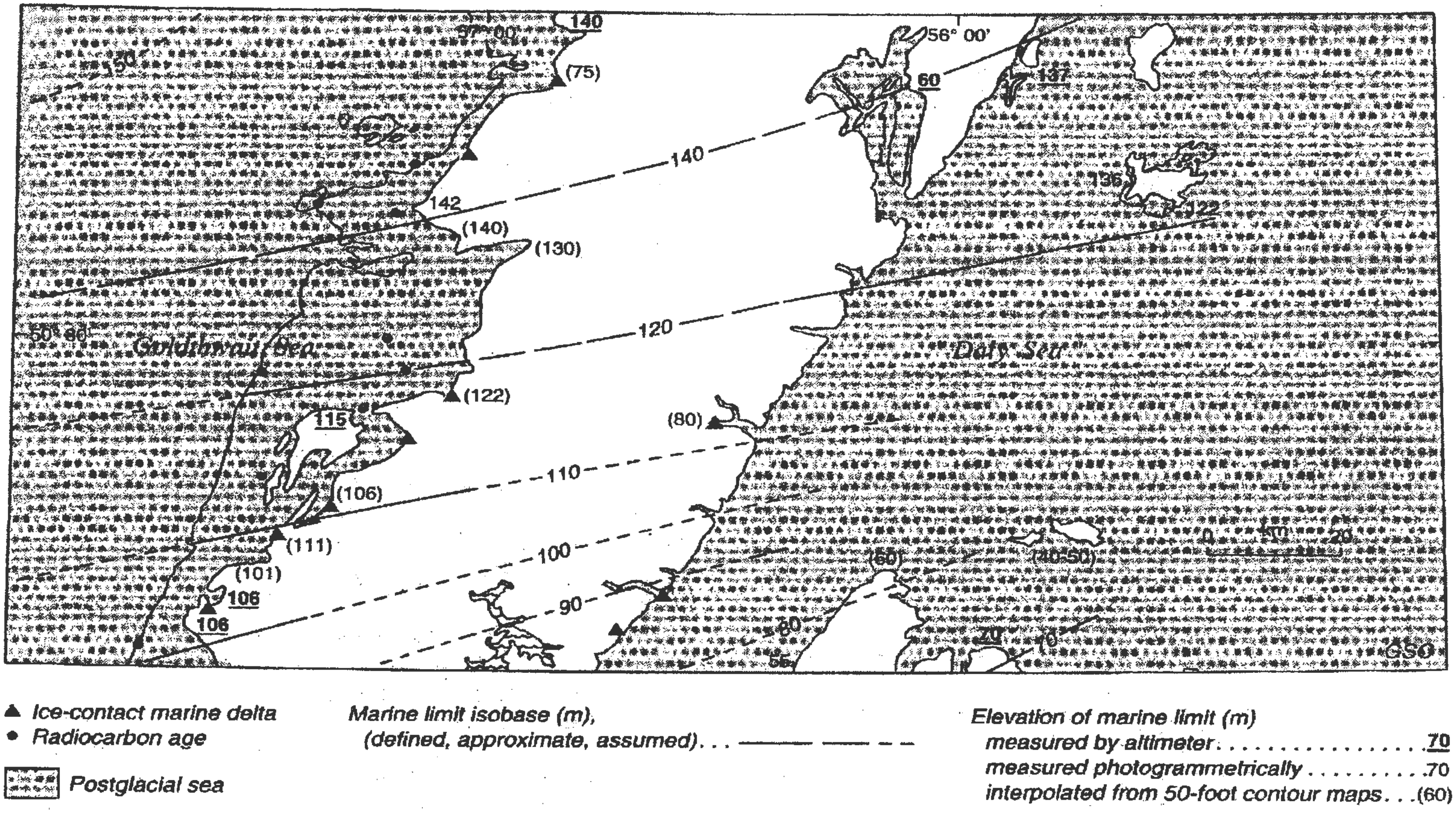

Figure 3.5: Extent of the postglacial Goldthwait Sea and Daly Sea. Marine limit gradient reflects greater ice loading to the west. (from Grant, 1994)

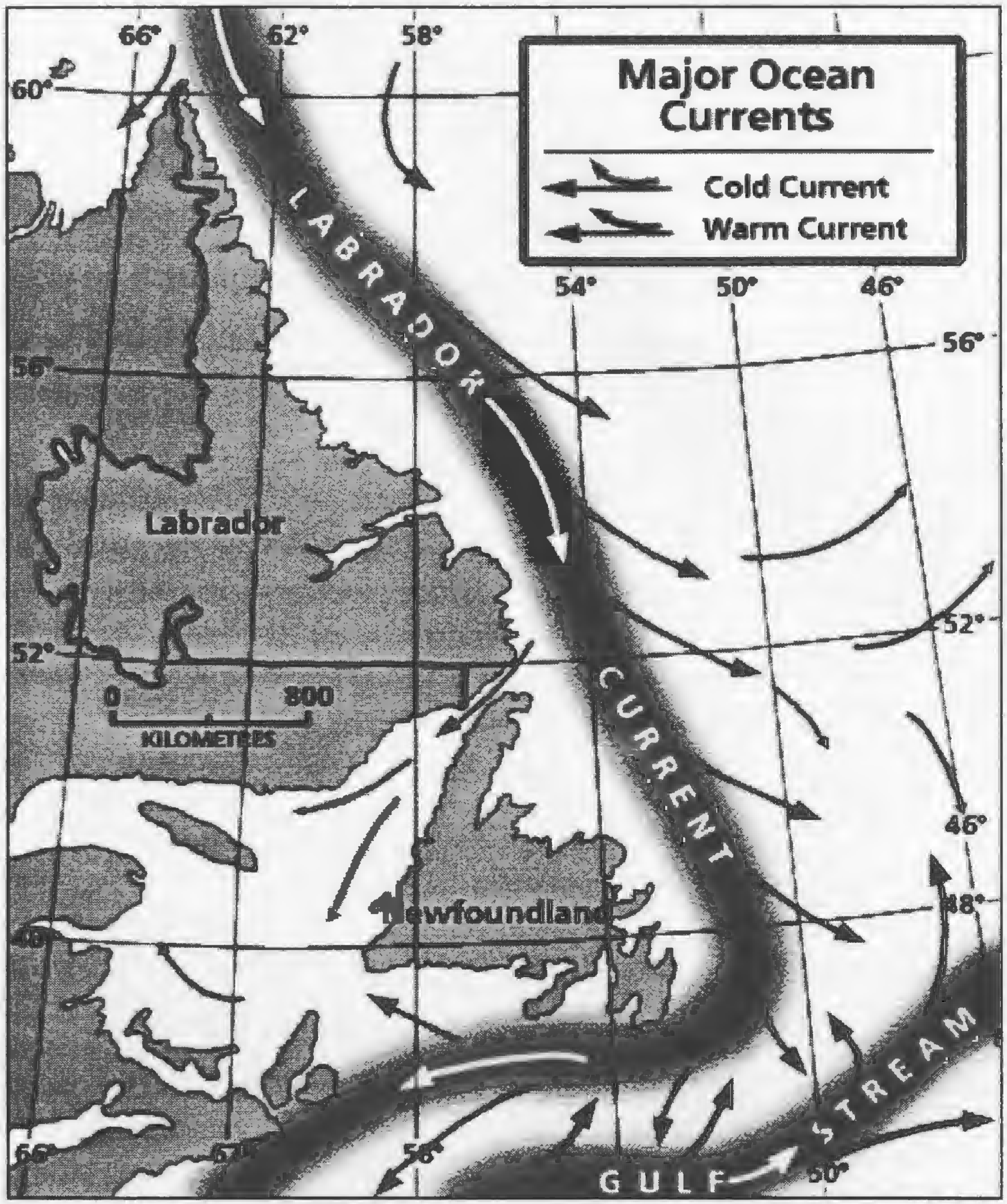

Figure 3.6: Major ocean currents.
The Labrador Current is cold, the Gulf Stream is warm.
(modified from McManus and Wood, 1991)

distinct bands, forming an inner and an outer branch (Farmer, 1981; Jordan, 1975). The inner band is a cold arctic current that moderates the climate of Newfoundland and Labrador, maintaining relatively cool temperatures year round, especially near the coast. The mean August sea surface temperature near the Grey Islands between 1855 and 1954 was 11° C (Mortsch *et al.*, 1985).

Banfield (1981) places the Grey Islands in the Northern Peninsula climatic zone (Fig. 3.7). Summers are short and cool with high average cloud cover, while winters are normally long and cold. The last spring frost typically occurs in the first weeks of June, while the first of the fall arrives in the last weeks of September. The mean daily air temperature of the warmest month (July) is 13°C, and annually there are an average of 900 degree days above 5°C. Winters are cold, but somewhat moderated by the surrounding ocean. The mean daily air temperature of the coldest month (February) is -8°C and there are an average of 900 degree days below 0°C. Temperatures are progressively lower from south to north on the peninsula. Average annual precipitation is near 1500 mm. Nearby climatological stations report 67-78% winter precipitation falling as snow (Banfield, 1981). The median number of days with snow cover is 150 to 180 (Damman, 1983).

The Northern Peninsula ecoregion has one of the shortest vegetative seasons on the island (based on a threshold temperature of 5.5°C), ranging from 150 days in the south to less than 110 in the north. This dramatic decrease in length of the vegetative season illustrates the Northern Peninsula's remarkable south to north climatic gradient (Damman, 1983).

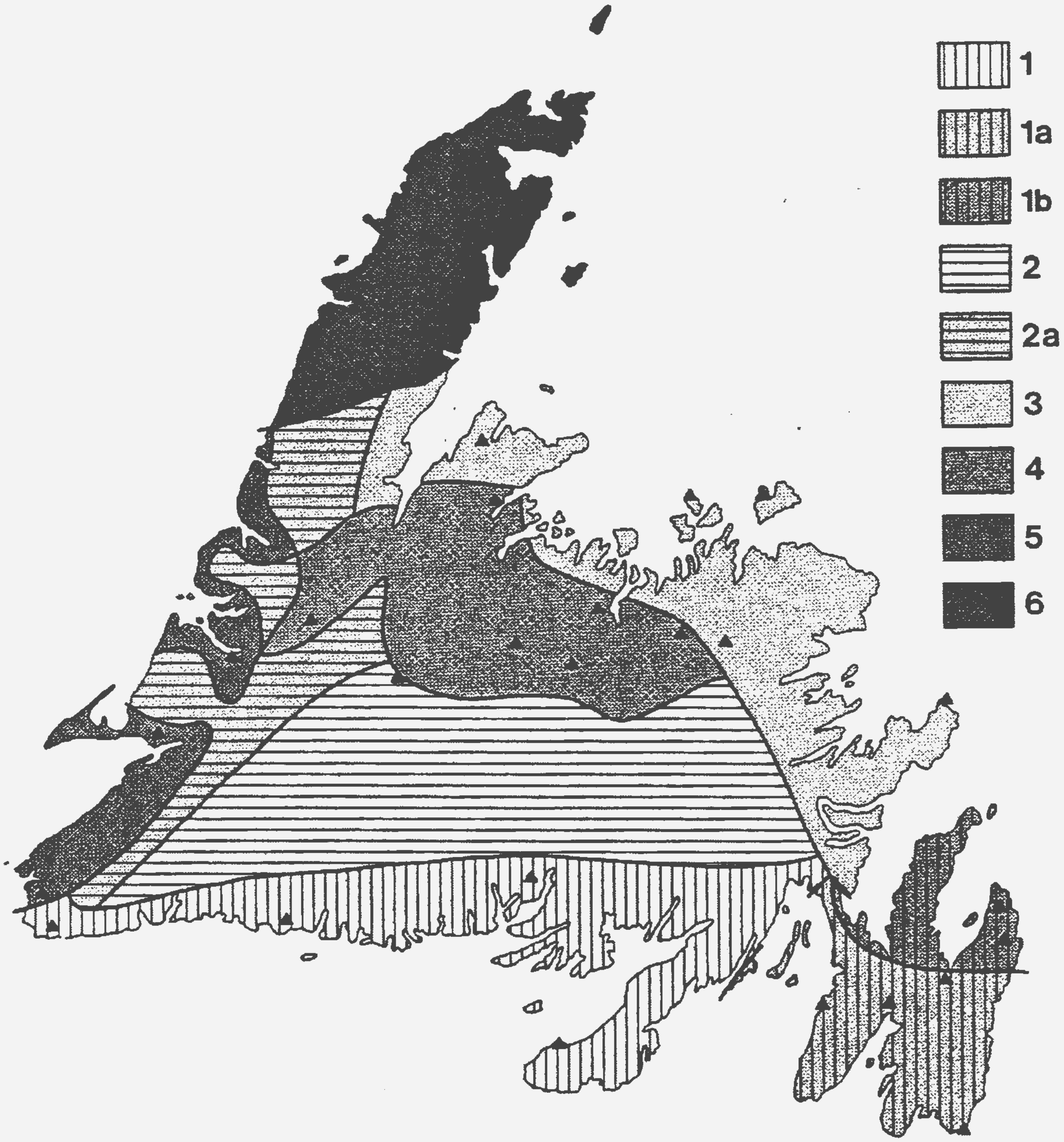

Figure 3.7: Climatic zones of Newfoundland, key next page. (modified from Banfield, 1983)

Key to Figure 3.7

1, 1a, 1b. South and south-east coasts and immediate hinterlands (subdivisions are based upon winter temperatures).

2, 2a. Central uplands (2), western hills and mountains (2a).

3. East coast and hinterlands.

4. Central lowlands.

5. West coast (Bonne Bay and south).

6. Northern Peninsula. Progressively colder at all times of year towards north of peninsula. Annual precipitation near 1500 mm. Winters long and cold, with continuous snow cover duration averaging up to 3 months in extreme north. Summers short and cool with high average cloudiness, especially over Long Range Mountains; occasional warm days near 25° C at coastal locations during offshore airflow.

3.7 Vegetation

The Grey Islands are part of the "northern coastal" subregion of the "Northern Peninsula Forest" ecoregion (Damman, 1983; Fig. 3.8). In this ecoregion as a whole, balsam fir (*Abies balsamea*) dominates the forests, while black spruce (*Picea mariana*) becomes important at higher elevations. Fire frequency is very low. The Northern Peninsula ecoregion is unique to the island, as many species of both trees and plants reach their northern limit at or near its southern boundary. This boundary, well south of the study site, represents the "most drastic climate-controlled change in the flora of the island", and many species which are common throughout Newfoundland (white pine, red maple, yellow birch, and trembling aspen among the most conspicuous) are absent here (Damman, 1983). Over 100 other plant species are either totally absent or are restricted to the very southern part of this ecoregion (e.g. *Osmunda regalis, Rhododendron canadense,* and *Viburnum cassinoides*).

Species which are not highly represented elsewhere on the island may be found in this ecoregion. Speckled alder (*Alnus rugosa*) swamps and thickets are replaced on the Northern Peninsula by those of mountain alder (*Alnus crispa*) or willow (*Salix*). The oval leafed bilberry (*Vaccinium ovalifolium*) is a common component of moist forests. Also more common in these forests than in other parts of the island are Canadian yew (*Taxus canadensis*), the tree dwelling lichen (*Nephroma arcticum*), and the blunt-leaf orchis (*Habenaria obtusata*) (Damman, 1983).

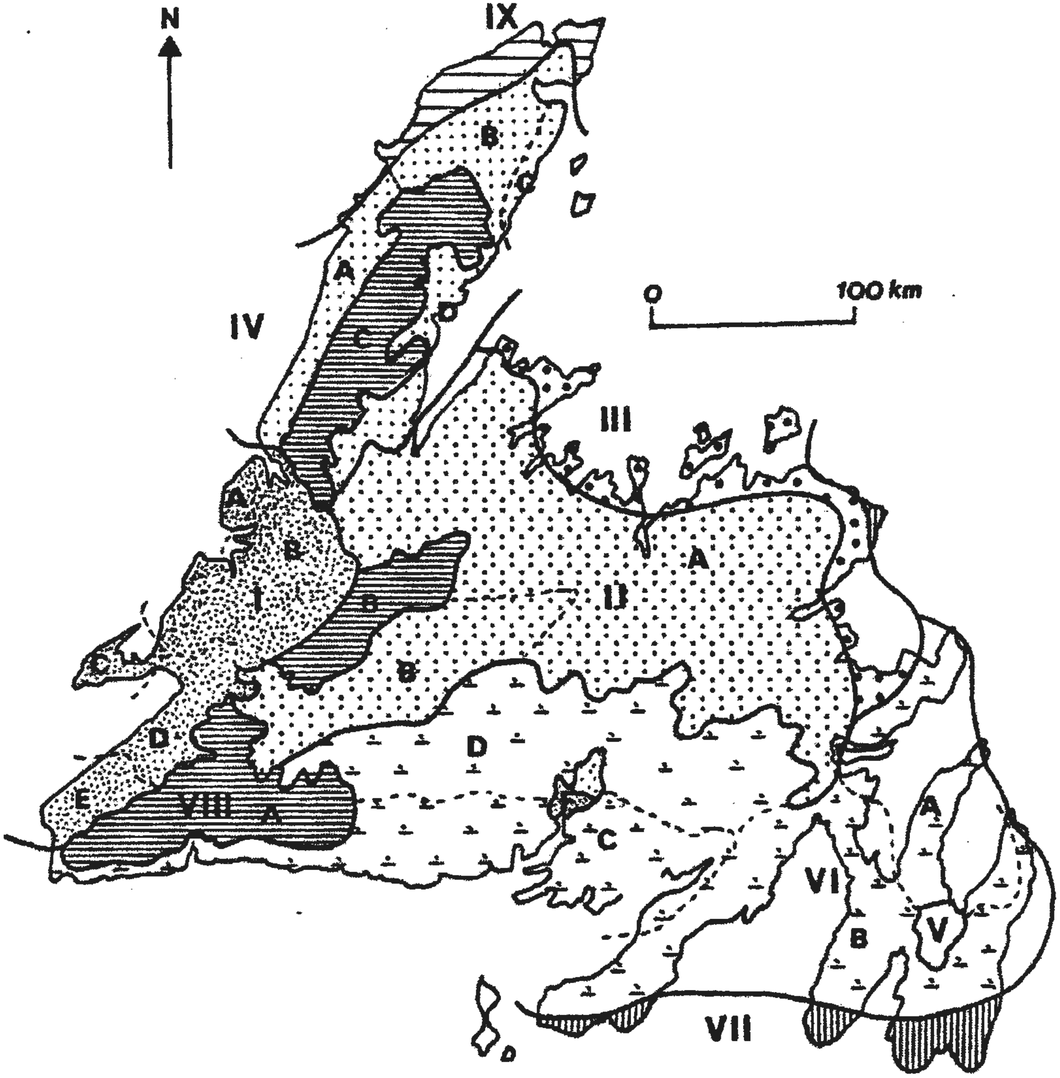

Figure 3.8: Ecoregions of Newfoundland.
(modified from Damman, 1983)

I = Western Newfoundland, II = Central Newfoundland, III = North Shore,
IV = Northern Peninsula, V = Avalon Forest, VI = Maritime Barrens,
VII = Eastern Hyper-oceanic Barrens, VIII = Long Range Barrens,
IX = Strait of Belle Isle

On the Grey Islands rocky dwarf shrub barrens are the dominant vegetation (Damman, 1983). Bell Island's vegetation consists largely of tuckamore with patchy areas of forest or bog. Vegetation around the site (Fig. 3.2) was described during the coring expedition. The forest on sheltered slopes near the site consists of black spruce (*Picea mariana*), birch (*Betula*), larch (*Larix*), and mountain ash (*Sorbus*). Alder (*Alnus*) is the predominant shrub. Tuckamore (krummholz) on the adjacent sphagnum bog and barrens includes black spruce, fir (*Abies*), juniper (*Juniperus*), sweet gale (*Myrica*), crowberry (*Empetrum*), laurel (*Kalmia*), lingonberry (*Vaccinium vitis-idæa*), and Labrador tea (*Ledum*).

CHAPTER 4 DESCRIPTION OF CORE

The following chapter provides a summary of findings resulting from the systematic analysis of the Grey Islands core. The observed sediment stratigraphy and loss-on-ignition results are followed by radiocarbon dates and a time-depth curve. The remainder of the chapter comprises a detailed description of the pollen record.

4.1 Stratigraphy and Loss-on-Ignition

The stratigraphy of the Grey Islands core and the percent loss-on-ignition curve are shown in Fig. 4.1. Below 700 cm in the core, sediment consists of clay-gyttja and sandy clay. Organic content in this lowest metre ranges from 1.7% to 4.4% ($\bar{x} = 2.8\%$). Above this layer are three metres of light brown gyttja (400-700 cm) overlain by dark brown gyttja for the remainder of the core (0-400 cm). Organic content in the lower light brown layer increases from 12.4% at its base to 29.3% at the transition to the darker, more organic, layer. Organic content in the upper four metres of the core ranges from 29.3% at the lower boundary to a maximum of 46.8% ($\bar{x} = 39\%$).

4.2 Radiocarbon Dates

Radiocarbon dates and calibrated age ranges are reported in Table 4.1. A time-depth curve summarizing sediment accumulation rates through the core was established from the radiocarbon ages and their associated depths (Fig. 4.2). The time-depth curve was constructed by directly linking the sampled radiocarbon dates to their associated depths in the core. This method was selected as being more accurate than fitting a regression model where there were only four established radiocarbon dates.

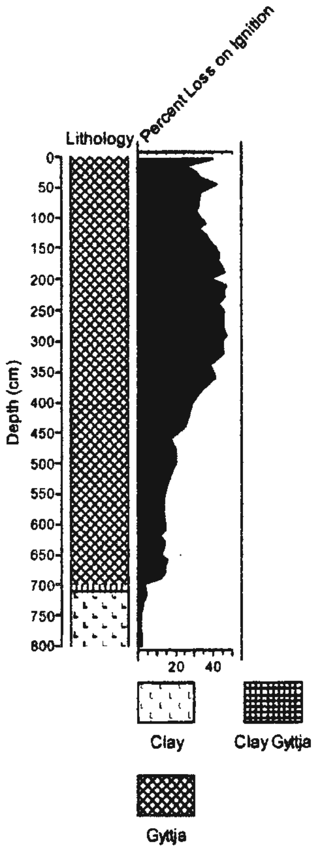

Figure 4.1: Lithology and loss on ignition.

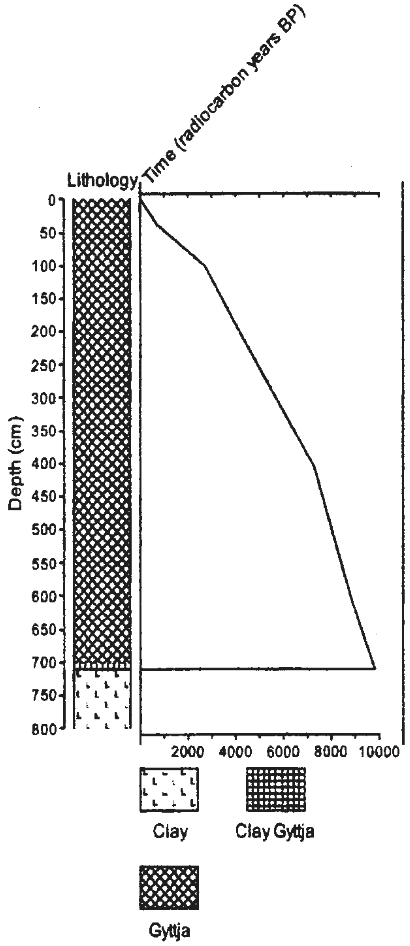

Figure 4.2: Time-depth curve.

Table 4.1 Radiocarbon Dates and Calibrations

Date (^{14}C years)[1]	Calibrated age range + Intercept (calendar years)[2]	Lab No.[3]	Depth in core (cm)	Material	Analysis performed
710 ± 50	693-645 (669)	TO-9238	39-44	Twig	AMS
2690 ± 80	2870-2745 (2808)	TO-9239	102-107	*Picea mariana* needles + twig	AMS
4320 ± 90	5045-4819 (4932)	GSC-5665	210-215	Bulk sediment	Conventional
7310 ± 140	8208-7967 (8088)	GSC-5664	405-410	Bulk sediment	Conventional
8880 ± 200	10,192-9702 (9947)	GSC-5638	605-610	Bulk sediment	Conventional
9870 ± 170	11,648-11,106 (11,377)	GSC-4577	702-712	Bulk sediment	Conventional

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[1] The error for radiocarbon dates represents 68.3% probability. All dates were corrected for isotopic fractionation to a base of $\sigma^{13}C = -25‰$.

[2] ^{14}C dates were calibrated using the CALIB online programme (Stuiver and Reimer, 1993).

[3] Laboratory designations: TO, IsoTrace Radiocarbon Laboratory; GSC, Geological Survey of Canada Radiocarbon Laboratory.

4.3 Numerical Results

A summary pollen percentage diagram for the Grey Islands site is given in Figure 4.3, while complete percentage, concentration, and influx diagrams are included in the appendix (Figs. A.1, A.2, and A.3). Table 4.2 lists minor taxa which were counted but not included on the diagrams and Figure 4.4 provides a summary of charcoal representation through the core.

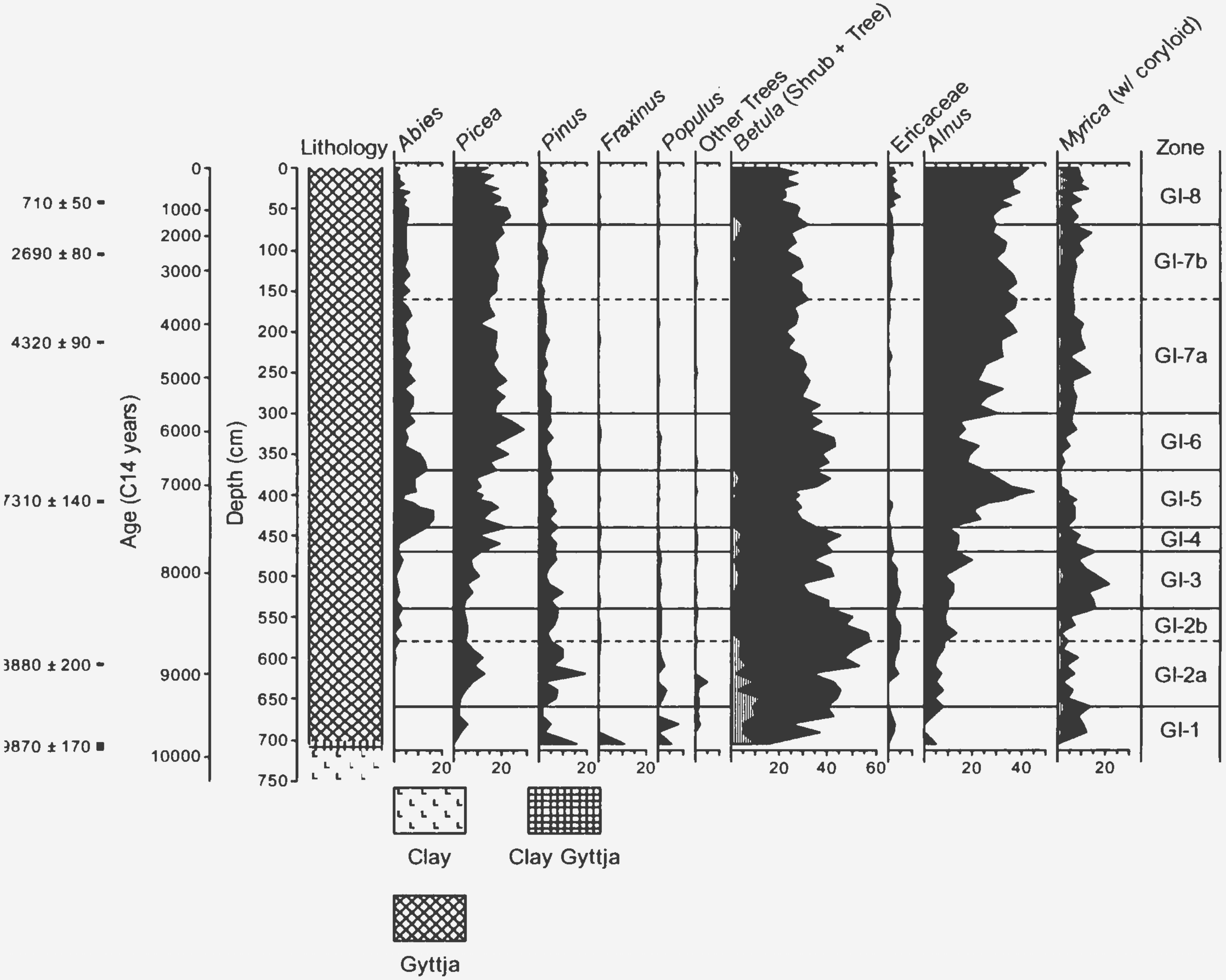

Figure 4.3: Grey Islands summary pollen percentage diagram, trees and shrubs.

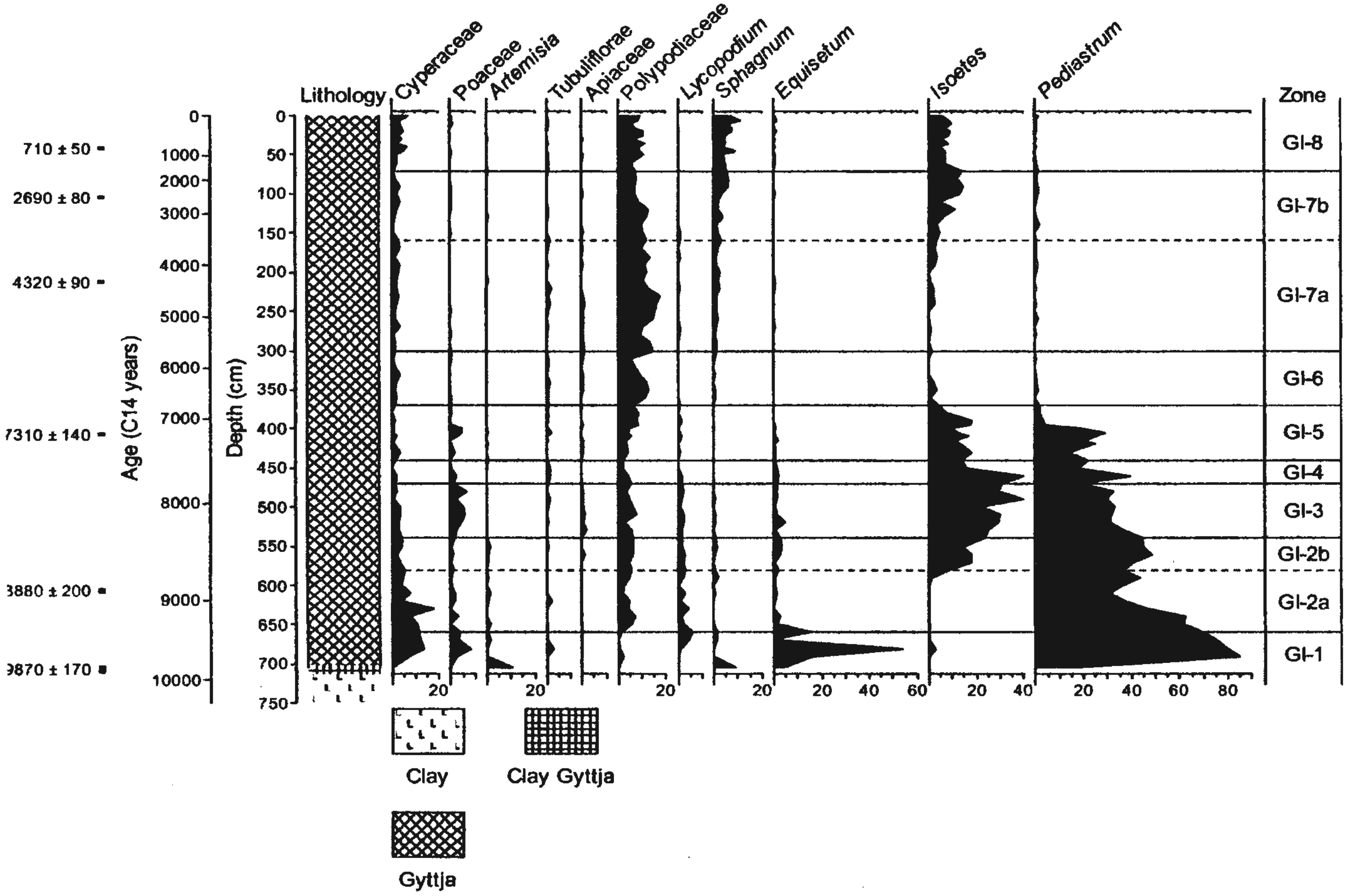

Figure 4.3 (cont.): Grey Islands summary pollen percentage diagram, nonarboreal pollen.

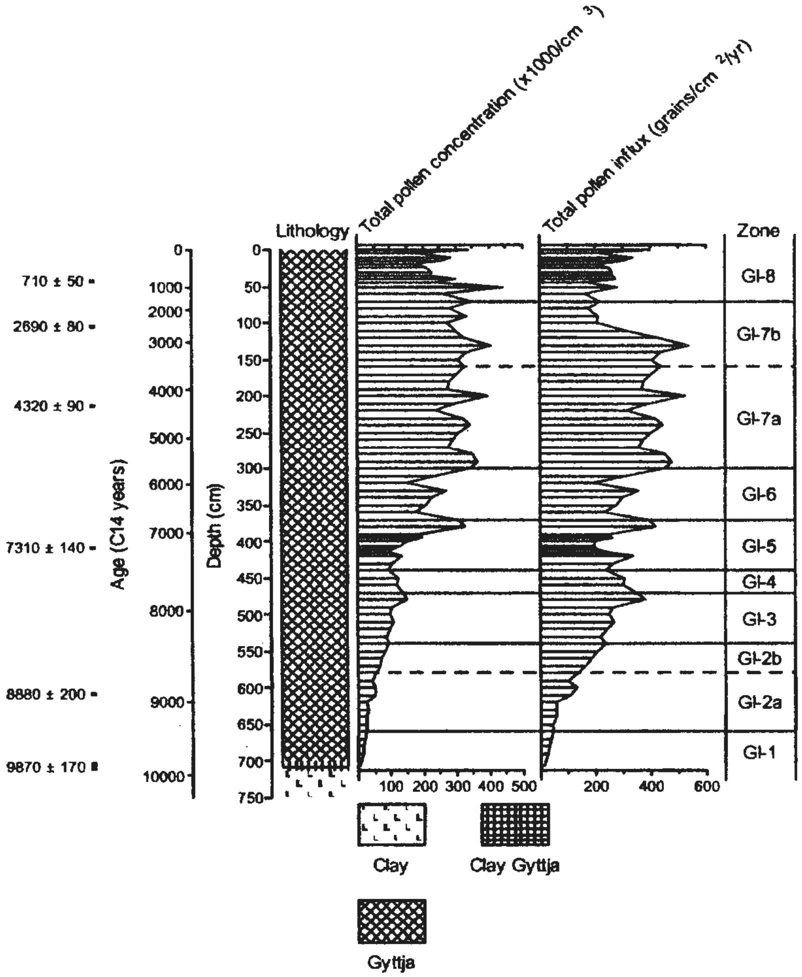

Figure 4.3 (cont.): Grey Islands summary pollen percentage diagram, concentration and influx.

Table 4.2 Minor Fossil Pollen Grain and Spore Types Identified

Trees (extra-regional sources, represented as "other trees" on pollen diagrams)

Acer
Castanea
Fagus
Quercus
Tsuga
Ulmus

Shrubs

Juglans
Ostrya

Herbs

Chenopodiaceae
Epilobium
Liguliflorae
Rosaceae
Rubiaceae
Rumex
Thalictraceae

Spores

Myriophyllum
Nuphar
Nymphaea
Osmunda

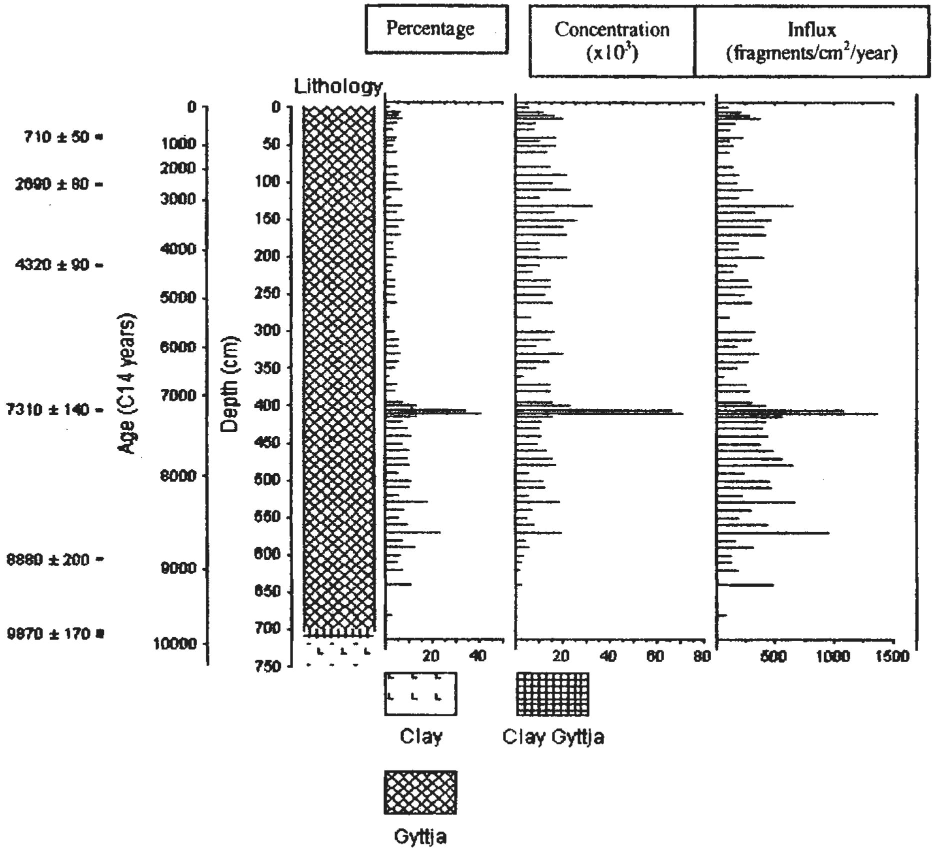

Figure 4.4: Charcoal percentage, concentration, and influx.

4.4 Pollen Assemblage Zones

The pollen diagrams from the Grey Islands core are divided into the following local pollen assemblage zones (Figs. 4.3 and A.1, A.2, A.3), numbered and defined from the base upward: GI-1 (below 660 cm; ends *ca.* 9400 BP), GI-2 (660-540 cm; *ca.* 9400-8400 BP), GI-3 (540-470 cm; *ca.* 8400-7800 BP), GI-4 (470-440 cm; *ca.* 7800-7600 BP), GI-5 (440-370 cm; *ca.* 7600-6700 BP), GI-6 (370-300 cm; *ca.* 6700-5700 BP), GI-7 (300-70 cm; *ca.* 5700-1600 BP), and GI-8 (70-0 cm; *ca.* 1600 BP-present).

Pollen assemblage zone GI-1: herbs-*Salix*-shrubs (below 660 cm, ends *ca.* 9400 BP). Overall percentages register false abundance of certain taxa in this zone, as total pollen concentrations and influx are lower than in any other zone. Total pollen concentration and influx increase up the zone. Concentration from 3,700 to 22,000 grns/cm^3 and influx from 705 to 4206 grns/cm^2/yr ($\bar{x}$ = 2,624 grns/cm^2/yr).

Herbaceous sources contribute 10-24% of the pollen in this zone, higher than at any other time in the core. Herbaceous pollen influx and concentration are moderate, in contrast to the very low values for trees and shrubs. Input is dominated by high proportions of Cyperaceae (up to 14%) and Poaceae (reaches its maximum of 8%). *Artemisia* peaks to its maximum (10%) at the very base of the core. Tubuliflorae attain their maximum (3%) shortly thereafter.

Shrubs contribute 38-54% of the pollen in this zone. *Salix* attains its maximum percentages (up to 37%) at the base, decreasing irregularly to 15% at the top of the zone. Shrub birch (grain size <20μm) exhibits some of its highest percentages (5-10%) through this zone. *Juniperus* and *Cornus* reach maximum percentages (both 3%) near the top of the zone. The latter of the two is not well-represented outside of this zone. *Myrica* maintains relatively high percentages (7-11%) here. Grains assigned to the "Coryloid type" category reach 4% and are most likely degraded *Betula* or *Myrica*. They maintain a relatively consistent presence throughout the core. Ericaceae are also present (to 3%).

At this early stage in vegetation development, it is probable that all arboreal grains were carried in from distant sources and that no trees were actually growing in the area at the time. Extra-regional *Pinus* (up to 16%) dominates the arboreal component of the zone. *Picea* exhibits a small midzone peak (to 5%). *Fagus* (2%), *Castanea* (3%), and *Fraxinus* (11%), none of which are present on the Northern Peninsula, as well as *Populus* (8%), attain maximum percentages in this zone and have minimal representation elsewhere in the core.

This zone also registers high frequencies of *Sphagnum* (up to 9%) at the base of the core, followed by a maximum of *Lycopodium* (6%) at the transition to zone GI-2. *Equisetum* peaks twice in this zone, once to its maximum (54%) midzone, and again at the upper zone boundary (16%). *Pediastrum* is very high throughout, attaining maximum proportions (85%) midzone. *Isoetes* exhibits a small midzone peak (3%).

<u>Pollen assemblage zone GI-2</u>: *Betula-Picea* (660-540 cm; *ca.* 9400-8400 BP). Significant increases in the contribution of *Betula* and *Picea* pollen mark the transition to this zone. Concentration continues to increase up the zone from 22,000 to 55,000 grns/cm^3. The influx curve shows the same pattern, increasing from 4,206 to 23,361 grns/cm^2/yr ($\bar{x}$ = 13,156 grns/cm^2/yr). Charcoal makes its first significant appearance in

the core in this zone, increasing from 2,100 to a peak of 20,000 fragments/cm^3 in the lower half of subzone GI-2b.

This pollen zone is divided into two subzones: GI-2a, *Betula-Picea*-Cyperaceae (660-580 cm; *ca.* 9400-8700 BP); GI-2b, *Betula-Alnus-Picea* (580-540 cm; *ca.* 8700-8400 BP).

Subzone 2a: A decrease in shrub pollen percentages (down to 25%) and a relatively high contribution of arboreal pollen (4-38%) characterize this subzone. *Betula* increases to 53% at the upper subzone boundary. Its concentration and influx also increase through the subzone, rising steeply at the top (concentration to 30,000 grns/cm^3; influx to 3,755 grns/cm^2/yr). Some of this may be attributed to shrub birch which remains a strong presence in the subzone, attaining a maximum value of 12%. Birch grains <20µm are classified as shrub birch, >25µm as tree birch, and between 20 and 25µm as indeterminate (after Dyer, 1986).

Picea exhibits a significant increase in percentage (from 2 to 12%), though this probably continues to represent extra-regional input, as these gains are not matched in its concentration and influx curves. *Pinus* attains maximum percentages (up to 20%), along with some minor extra-regional taxa, namely *Quercus* (5%) and *Tsuga* (2%). The latter two are not a significant component in the percentage diagram at any other time. *Populus* is still present. *Abies* makes its first appearance near the upper subzone boundary with percentage reaching 2% and influx at 137 grns/cm^2/yr.

Herbaceous pollen decreases in frequency from 19% at the base of the subzone to 6% at the upper transition, while concentration and influx are moderate and relatively stable. Cyperaceae peak to their maximum percentage (18%) midzone then decrease to 6% at the upper subzone boundary, not mirrored in their moderate concentration and influx curves. Poaceae percentages are greatly reduced from zone GI-1 (down to <1%). *Artemisia* is still present in very small numbers through zone GI-2. Some minor taxa significant only in this subzone, namely Rosaceae and Chenopodiaceae, attain their maximum percentages (both 3%) near the base of the zone, while Tubuliflorae experience a small midzone peak (2%).

Proportions of *Salix* (down to 3%) and *Myrica* (down to 2%) have decreased from zone GI-1, though their concentration and influx curves, while low, remain quite stable. Ericaceae are absent from the lower half of this subzone, but reappear in relatively high frequencies (2-4%) midzone, accompanied by steadily increasing concentration and influx. The frequency curve for *Alnus* is stable, maintaining moderate percentages (4-9%), but with very low concentration and influx.

Polypodiaceae and *Lycopodium* are present in relatively high frequencies (both to 6%). After dropping off at the base of the zone, *Sphagnum* reappears in very small proportion (2%) near the upper subzone boundary. *Equisetum* shows a marked decrease from zone GI-1 (to <1%) while *Pediastrum* also exhibits a decline (to 31%), though much less significant.

Subzone GI-2b: This subzone is characterized by gradually increasing shrub pollen percentages (from 25 to 36%) and a significant contribution of *Betula* pollen (peaking at 56%). *Betula* percentages are very high in this subzone (39-56%), while those grains which can be definitively classified as shrub birch decrease significantly in percentage (to <1%), concentration (2,300 to 300 grns/cm^3), and influx (298 to 33 grns/cm^2/yr). At this level, however, a large proportion of intermediate birch grains (20-25µm) are still likely to represent shrub species.

The cumulative shrub pollen curves exhibit increases in percentage, concentration, and influx through this zone. *Alnus* shows a significant increase in concentration (from 4,900 to 9,200 grns/cm^3) and influx (from 618 to 1,176 grns/cm^2/yr), along with a small peak in percentage (to 14%). Ericaceae attain their maximum frequency (5%) midzone, reflected in muted form in the influx and concentration curves. *Myrica* begins a midzone increase in all graphs: percentage from 1 to 15%, concentration from 600 to 13,800 grns/cm^3, and influx from 82 to 1,764 grns/cm^2/yr. *Salix* is still present and exhibits a slight increase in all graphs.

Arboreal sources contribute 11-19% of the pollen in this subzone, a large part of which can be attributed to extra-regional *Pinus*, whose percentage, concentration, and influx curves mimic those of "trees" in general, increasing to the top of the zone. *Abies* makes very small gains in all graphs, while *Picea* remains stable.

Herbs contribute 6-9% of the pollen in this subzone, Cyperaceae being the only taxa of any note, with moderate values on all graphs. Rubiaceae are also present in this and the next zone, but in very small proportions (<2%). Polypodiaceae exhibit relatively high and stable percentages (5-7%), while *Lycopodium* decrease slightly near the upper zone boundary (to 2%). *Isoetes* and *Pediastrum* increase up the zone (8-23% and 37-49%, respectively). *Equisetum* maintains a small presence (1-3%).

Pollen assemblage zone GI-3: *Myrica*-shrubs-Poaceae (540-470 cm; *ca.* 8400-7800 BP). Concentration and influx increase through the zone: 84,800 to 151,600 grns/cm^3 and 21,460 to 38,311 grns/cm^2/yr ($\bar{x} = 27{,}611$ grns/cm^2/yr), respectively. Charcoal displays small peaks at the bottom (19,000 fragments/cm^3) and top (17,800 fragments/cm^3) of the zone.

A revitalised importance of shrubs and herbs, possibly at the expense of *Betula* which experiences a minor decrease, is characteristic of this zone. The contribution of shrubs has increased to 35-48% of the pollen in this zone, with corresponding gains in concentration and influx. *Myrica* attains maximum core values of both percentage (20%) and influx (2,767 grns/cm^2/yr) in the middle of the zone, along with a peak in concentration (21,700 grns/cm^3). Ericaceae reach maximum influx (615 grns/cm^2/yr) in the lower half of the zone, while *Salix* attains its maximum (1,006 grns/cm^2/yr) near the upper zone boundary. *Alnus* increases slightly with a peak (to 20%) near the top of the zone, reflected in all graphs. Shrub birch remains a presence at 1-5%.

Herbs constitute 4-11% of the pollen in this zone and achieve maximum influx values (1,950 grns/cm^2/yr) near the top, largely attributed to Poaceae which reaches its peak influx (1,258 grns/cm^2/yr) at the same time and contributes 2-7% of the herbaceous component. Cyperaceae maintain moderate and relatively stable levels. Apiaceae make a minor appearance (to 2%).

Arboreal pollen represents 14-23% of the total, increasing to the top of the zone. *Picea* experiences significant increases in all graphs through the zone: percentage (4-11%), concentration (3,700-16,000 grns/cm^3), and influx (470-2,034 grns/cm^2/yr). The upper zone boundary, at 470 cm, may indicate the time of true *Picea* arrival on Bell Island. *Abies* remains present in small numbers. *Betula* (indeterminate) frequencies have decreased in this zone (as low as 28%), though concentration and influx increase to the upper zone boundary.

Polypodiaceae and *Pediastrum* maintain relatively high percentages (3-8% and 19-44%, respectively) through the zone, and *Isoetes* reaches its maximum (40%).

<u>Pollen assemblage zone GI-4</u>: *Picea-Betula-Abies* (470-440 cm; *ca.* 7800-7600 BP). This zone is characterized by a decrease in shrubs and herbs, with a corresponding increase in trees, especially *Abies*, indicating initial establishment of boreal forest. There is a slight decrease in influx through the zone (from 35,201 to 23,766 grns/cm^2/yr; $\bar{x}$ = 29,884 grns/cm^2/yr), with the same pattern presented in the concentration curve (141,500-94,000 grns/cm^3). Charcoal concentration remains relatively stable, decreasing slightly to the upper zone boundary.

Arboreal sources contribute 22%-45% of the pollen in this zone, higher than at any other time in the core. *Picea* and *Pinus* proportions are quite high (22% and 8%, respectively). Tree *Betula* percentage, concentration, and influx decrease very slightly. *Abies* rises steeply from midzone in percentage (1-14%), concentration (1,800-12,800 grns/cm^3), and influx (226-1,632 grns/cm^2/yr).

Shrubs decrease from 39% at the base to 19% at the top of the zone, with corresponding declines in concentration and influx. *Myrica* (14-4%), *Salix* (3-2%), *Alnus* (10-14%), shrub birch (5-2%), and Ericaceae (2-1%) decrease through the zone in all graphs. Herbs exhibit the same decline (6-2%), due to decreases in Poaceae (2-0%) and Cyperaceae (2-1%) seen in all graphs.

Polypodiaceae (6-2%), *Lycopodium* (2-<1%), *Isoetes* (40-14%), and *Pediastrum* (40-22%) all decrease in the upper half of the zone.

Pollen assemblage zone GI-5: *Alnus*-*Abies*-Poaceae (440-370 cm; *ca.* 7600-6700 BP). This zone is characterized by a midzone drop in arboreal pollen with a corresponding peak in shrubs and herbs associated with a dramatic charcoal peak (to 71,400 fragments/cm^3) at approximately 7300 BP. Total pollen concentration and influx decrease into, and increase sharply out of, the middle of the zone: concentration decreases to 97,600 grns/cm^3, then increases to 326,000 grns/cm^3; influx decreases to 19,161 grns/cm^2/yr, then increases to 41,727 grns/cm^2/yr ($\bar{x}$ = 27,274 grns/cm^2/yr).

The percentage of shrubs increases from 19% at the base of this zone to 50% midzone, and decreases to 28% at the top. This can be attributed to similar changes in *Alnus*, rising from 10% at the base to its maximum of 45% midzone, and decreasing to 25% at the upper zone boundary. Its concentration and influx, however, increase dramatically through the zone (9,400-99,900 grns/cm^3 and 1,194-6,516 grns/cm^2/yr). *Myrica* decreases to the top of the zone (7-<1%), mirrored in the concentration and influx curves, and *Salix* decreases (2-<1%) to almost zero in the top half of the zone.

Arboreal percentage drops from 45% at the base of the zone to 20% midzone, then increases back to 37% at the upper zone boundary. This pattern is mirrored in the concentration and influx curves. *Abies* attains its peak percentage (17%) and influx (2,825 grns/cm^2/yr) in the lower half of the zone, and arrives at peak concentration

(41,900 grns/cm^3) at the upper zone boundary. *Picea* and *Pinus* maintain relatively high percentages (8-22% and 3-8%, respectively) and their concentrations rise steeply near the top of the zone (13,400-54,200 grns/cm^3 for *Picea*; 4,900-19,200 grns/cm^3 for *Pinus*). *Betula*, both shrub and indeterminate, exhibit the same pattern as the other graphs, decreasing and rising out of midzone, with a sharp increase in concentration to the upper zone boundary.

Herbs display the same general pattern as that for shrubs, increasing from 2 to 8% midzone, then decreasing to 1% at the top of the zone. Poaceae have a midzone resurgence, in conjunction with the *Alnus* peak and arboreal decline, peaking to 5%, 7400 grns/cm^3, and 483 grns/cm^2/yr. Cyperaceae are still present in low numbers (1-4%).

Polypodiaceae increase through the zone (2-8%). *Isoetes* (18-4%) and *Pediastrum* (29-2%) drop off near the top of the zone.

<u>Pollen assemblage zone GI-6</u>: *Picea-Abies-Betula* (370-300 cm; *ca.* 6700-5700 BP). This zone marks re-establishment of boreal forest with a decrease in shrubs and a corresponding increase in trees, especially *Picea* and *Betula*. Total pollen concentration and influx curves have a minor midzone peak, attributable to a peak in *Alnus*. Concentration ranges from 176,900 to 346,800 grns/cm^3, influx from 19,477 to 45,093 grns/cm^2/yr ($\bar{x}$ = 31,248 grns/cm^2/yr). Charcoal concentration remains relatively stable through this zone.

Arboreal sources contribute 25-40% of the pollen in this zone. *Picea* attains maximum percentages (up to 29%), matched by large increases in its concentration (to 61,100 grns/cm^3) and influx (to 3,986 grns/cm^2/yr). *Abies* decreases to the middle of the zone (from 14-4%), then increases slightly to the top (6%), observed more dramatically in its concentration and influx curves. *Pinus* remains a consistent component of the pollen sum (3-6%). *Betula*, more likely to be tree birch at this stage of forest development, maintains consistently high percentages (30-42%).

Shrubs experience a general decline from the previous zone (28 to 18%), but rise again at the upper zone boundary and into zone GI-7, mostly due to *Alnus* which exhibits the same pattern (25 to 15%). Shrub birch also decreases from 2 to <1%. *Myrica* increases dramatically in all graphs through the zone: percentage from <1 to 8%, concentration from 1,600 to 22,400 grns/cm^3, and influx from 107 to 1,464 grns/cm^2/yr.

The contribution of herbs (3-5%) is quite low now, while concentration (13,500 grns/cm^3) and influx (878 grns/cm^2/yr) are slightly higher than in the previous zone, attributable to corresponding increases in Cyperaceae. Percentage of Cyperaceae also increases slightly (1-4%). *Polypodiaceae* increases from the previous zone (6-15%), while *Isoetes* drops off completely at the middle of the zone (4-0%).

Pollen assemblage zone GI-7: *Picea-Betula-Alnus* (300-70 cm; *ca.* 5700-1600 BP). This zone is characterized by a steady increase in the representation of shrubs. Influx ranges from 17,646 to 53,741 grns/cm^2/yr ($\bar{x}$ = 37,490 grns/cm^2/yr).

This pollen zone is divided into two subzones: GI-7a *Picea-Betula-Alnus* (300-160 cm; *ca.* 5700-3500 BP); GI-7b *Picea-Betula-Alnus*-shrubs (160-70 cm; *ca.* 3500-1600 BP).

Subzone GI-7a: This subzone is characterized by a steady increase in the representation of shrubs due to increases in *Alnus*. Influx (31,353-52,492 grns/cm^2/yr; $\bar{x}$

= 41,232 grns/cm^2/yr) and concentration (241,700-396,700 grns/cm^3) are very high throughout this subzone. Charcoal concentration remains stable from the preceding zone.

Arboreal sources are responsible for 20-36% of the pollen in this subzone, and arboreal influx peaks to its maximum of 7,703 grns/cm^2/yr near the base of the zone. *Abies* is consistently present in relatively high percentages (2-8%), concentration ($\bar{x}$ = 19,800 grns/cm^3), and influx ($\bar{x}$ = 1,304 grns/cm^2/yr), decreasing slightly at the upper subzone boundary. *Picea* also maintains relatively high and stable percentages (11-22%), concentration ($\bar{x}$ =54,000 grns/cm^3), and influx ($\bar{x}$ =3,541 grns/cm^2/yr). *Pinus* decreases gradually in all graphs: percentage from 5 to 2%, concentration from 18,300 to 6,300 grns/cm^3, and influx from 1,196 to 416 grns/cm^2/yr. *Betula* also decreases slightly from 36 to 25%, mirrored in its concentration and influx curves.

Alnus increases from 22 to 38% through the zone. It also attains maximum values for concentration (151,000 grns/cm^3) and influx (10,002 grns/cm^2/yr). *Myrica* is more stable in its frequency curve, ranging from 4 to 12%, and it reaches its maximum influx value (2,474 grns/cm^2/yr) midzone. Coryloid type grains have a large resurgence, especially in concentration and influx. Ericaceae begin to increase slowly.

Herbaceous sources again constitute 2-5% of the total, increasing slightly from the base to the top of the subzone. Cyperaceae are consistently present in relatively high percentage (to 4%), concentration (to 11,700 grns/cm^3), and influx (to 775 grns/cm^2/yr). Tubuliflorae (2%), having been barely visible since the base of the core, peak to their maximum concentration (5,400 grns/cm^3) and influx (355 grns/cm^2/yr).

Polypodiaceae peaks midzone to its maximum frequency (17%) while *Sphagnum* and *Isoetes* increase slowly to the top of the subzone (1 to 3% and <1 to 3%, respectively).

Subzone GI-7b: Total pollen influx peaks to its maximum of 53,741 grns/cm^2/yr in the lower half of this subzone, then drops off dramatically in the upper half of the zone. Concentration is high throughout (to 406,900 grns/cm^3). Charcoal concentration, having risen again just below the lower zone boundary, exhibits a small peak midzone (33,100 fragments/cm^3) and remains relatively high to the top of the core.

Arboreal sources contribute 20-28% of the pollen in this subzone, primarily attributable to *Picea* (14-20%) and *Abies* (2-7%). Both exhibit high concentrations throughout, but experience a drop in influx at the upper half of the subzone. *Pinus* has decreased slightly (1 to 4%) from the previous subzone, while *Betula* percentages remain relatively strong, though also decreasing slightly overall (32 to 21%). Following the overall trend in total pollen influx, *Betula* influx drops off dramatically in the upper half of the zone (from 6,941 to 1,925 grns/cm^2/yr) .

Shrub pollen constitutes 40-49% of the total, dominated again by *Alnus* (28-32%). *Myrica* is also a large component of the shrub total in this subzone (5-11%). The influx curves for *Alnus* and *Myrica* show a decrease in the upper half of the zone (to 2,538 grns/cm^2/yr and 546 grns/cm^2/yr, respectively), but this is not matched in their percentage or concentration curves. Concentration of *Myrica* actually increases near the upper zone boundary (to 30,300 grns/cm^3). Shrub birch increases from midzone (to 5%) and attains maximum values for concentration (17,100 grns/cm^3) and influx (546 grns/cm^2/yr). Ericaceae and coryloid type grains also increase through the zone.

Herbs contribute 1-5% of the pollen in this subzone, primarily reflecting Cyperaceae (1-4%) which experiences a decrease near the upper zone boundary, but rises again into the next zone. *Artemisia*, with very small percentages (up to 1%), reaches its peak concentration (4,000 grns/cm^3) and influx (263 grns/cm^2/yr) in the lower half. *Sphagnum* increases up the zone (2-6%), while Polypodiaceae decreases slightly (12-7%). *Isoetes* also increases (3-14%).

<u>Pollen assemblage zone GI-8</u>: *Alnus*-Cyperaceae-shrubs (70-0 cm; *ca.* 1600 BP to present). This zone is characterized by an increase in shrubs and herbs at the expense of trees. Influx is lower than at any time since zone GI-2b (8700-8200 BP), ranging from 16,486-39,775 grns/cm^2/yr ($\bar{x}$ = 25,477 grns/cm^2/yr). Concentration decreases to the middle of the zone and rises again to the top of the core (177,000-340,800 grns/cm^3), but without attaining the value of preceding zones.

Arboreal pollen decreases in proportion from 32% near the base of the zone to 14% near the top, while shrub pollen increases from 42% at the base to 55% at the top, and herbs from 2 to 8%. The shrub component in this uppermost zone is dominated again by *Alnus* (increasing from 29 to 43% through the zone), but also receives important contributions from *Myrica* (increasing from 3 to 8%), coryloid type grains, and Ericaceae (both to 5%). Concentration and influx of *Alnus* and *Myrica* also increase to the top of the core. Shrub birch decreases in this zone from 5 to <1%, concentration from 3,200 to 1,100 grns/cm^3, and influx from 546 to 63 grns/cm^2/yr.

Herbs also increase rapidly in all graphs out of the previous zone and continue to increase to the top of the core. Cyperaceae increases from 1 to 7%, while also attaining maximum values for concentration (23,700 grns/cm^3) and influx (1,378 grns/cm^2/yr).

Though somewhat sporadic in their graphs, *Picea* and *Abies* experience a decline in all curves. *Picea* percentage decreases from 23 to 9%, concentration from 96,100 to 16,000 grns/cm^3, and influx from 3,058 to 946 grns/cm^2/yr. *Abies* percentage decreases from 6 to 1%, concentration from 25,300 to 1,700 grns/cm^3, and influx from 805 to 98 grns/cm^2/yr. *Pinus* decreases from midzone: frequency from 4 to 1%, concentration from 10,000 to 4,300 grns/cm^3, and influx from 575 to 151 grns/cm^2/yr. *Betula* maintains relatively strong percentages (19-28%) and influx (2,115-3,983 grns/cm^2/yr), though its concentration drops sharply midzone.

Sphagnum exhibits very high percentages (4-11%) which rise to the top of the core. Polypodiaceae (6-11%) and *Isoetes* (5-14%) are also high through this zone.

CHAPTER 5 VEGETATION RECONSTRUCTION

5.1 Vegetation Reconstruction and Regional Analogues

A summary Table of vegetation at the site by zone is given in Table 5.1, while a regional comparison of postglacial vegetation development may be found in Table 5.2.

Zone GI-1 herbs-*Salix*-shrubs (ended *ca.* 9400 BP):

This initial pollen assemblage indicates that, following emergence from the postglacial Daly Sea, the site was receiving inputs from locally-growing herb and shrub species, as well as from extra-regional arboreal sources. The vegetation was an open tundra community dominated by sedges, grasses, and other herbs, with dwarf willow as the dominant shrub. *Lycopodium*, associated with arctic or alpine conditions (Jordan, 1975), is prevalent here. The assemblage is similar to those from modern sedge-dominated tundra communities (Lamb, 1980) and may be somewhat analogous to the modern tundra of north-central Labrador-Ungava (Hare, 1959) or southern to central Baffin Island (Macpherson, 1982; Vilks and Mudie, 1983). However, direct numerical comparisons with the modern spectra are unlike any found today (Engstrom and Hansen, 1985), probably due to temporally unique processes of soil maturation and plant migration (Lamb, 1984).

In Newfoundland, Macpherson's (1982) sedge-willow zone (ended *ca.* 9270 BP) from a site on the Avalon Peninsula, closely resembles GI-1. Concentration at the Avalon site increases from 3,000-20,000 grns/cm^3, very similar to the 3,700-22,000 grns/cm^3 range of GI-1. The most important species are *Salix*, Cyperaceae, Ericales,

Table 5.1 Site Vegetation by Zone

Zone	Depth (cm)	Age (years BP)	Name	Vegetation
GI-8	70-0	1600 - present	*Alnus*-Cyperaceae-shrubs	A more open woodland vegetation continues to present. Sphagnum remains important, while tree populations decline, making way for shrubs and herbs to fill spaces in the woodland.
GI-7	300-70	5700-1600	*Picea-Betula-Alnus*	An early opening of the forest with increased alder and sweet gale is followed at 2500 BP by a major deterioration. A large increase in Sphagnum registers a regional onset of paludification at this time.
GI-6	370-300	6700-5700	*Picea-Abies-Betula*	Closed crown boreal forest dominated by spruce with patches of birch and fir. Fir has declined as it was outcompeted by spruce in marginal habitats.
GI-5	440-370	7600-6700	*Alnus-Abies*-Poaceae	Local fire at 7300 BP alters normal sequence from open woodland to boreal forest. Trees are partially replaced by shrubs and herbs. The developing forest is re-established near the end of this zone.
GI-4	470-440	7800-7600	*Picea-Betula-Abies*	Open woodland with an understorey of shrubs. Major components of the boreal forest are in place. Spruce and fir are established. Fir is of greater importance than in the modern boreal forest.
GI-3	540-470	8400-7800	*Myrica*-shrubs-Poaceae	Continuously evolving shrub dominated landscape into which trees are migrating. Spruce was present locally by the end of the zone.
GI-2	660-540	9400-8400	*Betula-Picea*	Low sedge-shrub tundra transforming into a low arctic dwarf-shrub tundra. Increasing importance of alder, sweet gale, Ericales, and shrub birch.
GI-1	base - 660	ends ca. 9400	herbs-*Salix*-shrubs	Open tundra community dominated by sedges, grasses, and other herbs. Dwarf willow was the dominant shrub.

Table 5.2 Regional Postglacial Vegetation

Time (yrs BP)	Grey Islands	Northern Peninsula	Baie Verte Peninsula	Southeastern Labrador	Offshore Pollen Records	Molluscan Assblgs.	Dinocyst Assblgs.
present	Paludification	Paludification	Deterioration of Boreal Forest	Deterioration of Boreal Forest	Deterioration of Boreal Forest	Boreal species	Modern SSTs Established
1000			Fire				
2000	Boreal Forest		Boreal Forest				
3000		Boreal Forest					
4000				Boreal Forest	Boreal Forest	Arctic and Boreal species	
5000		Fire					
6000	Fire				Shrub Tundra		Slight Warming of SSTs
7000	Shrub Tundra	Herb and Shrub Tundra					
8000			Shrub Tundra	Shrub Tundra	Herb Tundra		
9000	Herb Tundra			Herb Tundra		Arctic species	Arctic Conditions
10000							
11000			Herb Tundra				
12000							

Poaceae, and *Artemisia*, all at similar frequencies to those in GI-1. *Lycopodium* and shrub birch increase in this zone at both sites. There is also a great deal of extra-regional arboreal pollen input at the Avalon site, especially from *Pinus*, *Picea*, and *Betula*. Some differences lie in the importance of *Ulmus*, not present in GI-1, and in the lack of *Populus, Fraxinus, Fagus, Castanea, Juniperus,* and *Myrica* grains. Macpherson (1982) compares this assemblage to the intermediate arctic tundra of central Baffin Island.

Zone GI-1 can also be compared with Anderson and Macpherson's (1994) diverse record and general summary of Newfoundland's vegetation during the 13,500-11,000 BP interval. Vegetation in the southwest of the island resembled a shrub dominated tundra composed of *Betula, Salix, Juniperus,* and Ericales, along with herbs like *Artemisia*, Cyperaceae, Poaceae, and Asteraceae. Aside from the latter, all of these species are important components of the vegetation in zone GI-1. But though the species are similar, GI-1 remains herb dominated. A sparse herb-low shrub tundra is found at herb dominated northeastern sites, but these differ from GI-1 in their inclusion of *Oxyria* and paucity of shrub birch. Extra-regional *Pinus* pollen is abundant in both, and northern lakes, like this one, supported abundant *Pediastrum*.

On the Northern Peninsula, Macpherson's (1997) 8000-7500 BP period shares similar proportions of *Salix*, Poaceae, shrub birch, *Lycopodium*, *Betula*, and extra-regional arboreal species with zone GI-1. However, *Juniperus* and *Artemisia* are absent here. Also, GI-1 has more Cyperaceae and *Myrica*, but fewer Ericales.

This assemblage also bears similarities to the early zones of studies from southeast Labrador. It is perhaps most analogous to an early zone (not dated, but >6000

BP) in Jordan's (1975) Alexander Lake study. Jordan notes high proportions of willow, sedges, grasses, Ericales, and *Artemisia*, as well as an extra-regional *Pinus* peak, all as exhibited in zone GI-1. *Picea* and *Abies* representation is insignificant in the curves of both studies, while alder and birch frequencies are moderate, signalling their approach. Jordan interprets this assemblage as a sedge-shrub tundra in more favourable exposures and a lichen-heath tundra in other locations.

Lamb's (1980) earliest zones at Whitney's Gulch and Paradise Lake (not precisely dated, but >9000 BP), southeast Labrador, are very similar to zone GI-1 except for the lack of a noticeable contribution from *Ranunculus*. Whitney's Gulch registers high basal values of *Salix*, along with grasses, dwarf birch, and Ericaceous shrubs, interpreted as an open tundra vegetation. Paradise Lake is rich in sedges and grasses, with overall pollen frequencies that are similar to modern sedge-moss tundra. Lamb believes that drier sites would support dwarf birch, willows, grasses, and *Artemisia*, while mineral-rich flushes sustained sedges and *Ranunculus*.

In the Lake Melville area of southeast Labrador Vilks and Mudie's (1983) 9000-7500 BP period is dominated by nonarboreal species, namely shrub birch, willow, sedges, grasses, *Lycopodium, Alnus,* and *Selaginella*, all but the last of which are common to zone GI-1. They describe the assemblage as representing "tundra vegetation" similar to the low arctic tundra of northern Ungava and southern Baffin Island.

Engstrom and Hansen (1985), in their southeast Labrador pollen studies, also recorded high frequencies of willow, sedges, and grasses from 10,500-9500 BP. Relatively high amounts of Tubuliflorae, Caryophyllaceae, and *Epilobium* were also noted. They define the vegetation at this time as an open tundra dominated by sedges, grasses, and other herbs with dwarf willow as the dominant shrub.

Levac and de Vernal (1997) took a marine sediment core from Cartwright Saddle, located off of the southeast Labrador coast, with an initial zone that also bears similarities to GI-1. Some of the same herb and shrub species are dominant, especially willow, sedges, Ericales, and Tubuliflorae. Differences lie in their identification of *Rumex* and *Glaux* pollen, as well as their lack of birch, *Juniperus*, and *Artemisia*.

Subzone GI-2a *Betula-Picea*-Cyperaceae (9400-8700 BP):

The vegetation in this subzone remains herb dominated and is a low sedge-shrub tundra. Though the percentage of shrubs and herbs has decreased, influx and concentration remain constant, suggesting that the percent decline is a result of input from extra-regional trees which are becoming established to the south. Judging by the overall vegetation composition at this time, it can be assumed that increases in 20-25 μm birch grains are still of the shrub variety.

This zone resembles the latter part of Macpherson's (1982) sedge-willow zone (ended *ca.* 9270 BP). Herbs and willow were important here, at the same time that shrub birch was demonstrating a marked increase in frequency. Macpherson suggests that this assemblage may be analogous to the low arctic tundra of northern Labrador.

Subzone GI-2b *Betula-Alnus-Picea* (8700-8400 BP):

The tundra is becoming increasingly shrub dominated, with noticeably elevated input from *Alnus, Myrica,* Ericales, and shrub birch. These are expanding from existing populations and migrating in, though sustained influx values for sedges, grasses, and willows indicate that these herbs and low shrubs were not displaced by the increase in shrub cover (Engstrom and Hansen, 1985). According to Engstrom and Hansen (1985), the composition of this assemblage is similar to the modern shrub tundra spectra of Labrador-Ungava, and Dyer (1986) also interprets it as a low-arctic dwarf-shrub tundra. Macpherson (1982) finds no modern analogue to this assemblage, but instead defines it as the start of a 1000 year period of continuously changing shrub vegetation into which trees are migrating.

Balsam fir has established a small, but continuous presence in all graphs, reflecting its northward migration on a regional scale. The occurrence of *Abies balsamea* with increasing *Alnus* is noted around 8000 BP at many sites in Labrador and may indicate a slight regional warming (Engstrom and Hansen, 1985).

Subzone GI-2b is roughly analogous to Engstrom and Hansen's (1985) 9500-8000 BP period from southeast Labrador. A decreasing percentage of herb taxa, accompanied by increased shrub frequencies, is indicative of both zones. But, like in GI-2b, the influx of herbs to Engstrom and Hansen's zone did not decrease. This points to an increase in overall abundance of shrubs, without any true decrease in the herb component. They interpret this assemblage as a tundra vegetation that is increasingly dominated by shrubs, though continuing to support a large population of herbs. It may be similar to the modern tundra spectra of Labrador-Ungava.

Similar replacement of herb dominated assemblages and increasing importance of shrubs, especially *Betula, Alnus, Salix,* and *Myrica*, is noted by Anderson and Macpherson (1994) in the 10,000-8000 BP interval. *Myrica* does not really gain importance in the Grey Islands' spectrum, however, until the top of this zone and into the next. Dyer (1986) interprets a similar zone in her study on the Baie Verte Peninsula (11,800-8500 BP) as a low arctic dwarf-shrub tundra. GI-2b also corresponds to the early part of Macpherson's (1982) birch-shrubs zone on the Avalon Peninsula (*ca.* 9300-8300 BP) of continuously changing shrub vegetation.

Zone GI-3 *Myrica*-shrubs-Poaceae (8400-7800 BP):

The vegetation in this zone is a continuation of Macpherson's (1982) 1000 years of evolving shrub dominated landscape into which trees are migrating. Alder representation increases to the top of the zone, evidenced by an increase in both concentration and influx, something which would have improved soil fertility through nitrogen fixation (Lamb, 1980). Spruce and balsam fir may have benefited from this, as spruce was present by the end of this zone, followed 200 years later by fir.

Ericales, shrub birch, *Alnus, Myrica, Lycopodium, Isoetes,* and *Juniperus* create the shrub dominated landscape in Macpherson's (1982) birch-shrubs zone (*ca.* 9300-8300 BP). Only *Juniperus* is not an important component of the vegetation in GI-3. The *Alnus* increase, followed by establishment of spruce and fir, is also noted in Lamb's (1980) southeast Labrador 8000-6000 BP period.

Zone GI-4 *Picea-Betula-Abies* (7800-7600 BP):

Forest cover is increasing now, causing shrubs and herbs to be gradually crowded and shaded out. Sedges, grasses, and shrubs exhibit a true decrease through the zone. *Picea* is locally established at the base of this zone, while *Abies balsamea* follows 200 years later. *Abies* pollen is rarely found beyond the range of the tree, indicating its establishment at the top of this zone (Engstrom and Hansen, 1985). The major components of the boreal forest are now in place, but the persistence of relatively large amounts of shrub birch and alder reveal that the forest remains somewhat open. Lamb (1980) describes this community as a "park tundra", while Macpherson (1982) interprets it as an open woodland with an understorey of shrubs.

GI-4 is similar to Engstrom and Hansen's (1985) 8000-6000 BP period. While the percentage of shrubs and herbs decline in southeast Labrador, *Picea* is established, followed 500 years later by *Abies*. A small peak in birch is also noted in both studies. The 20-25 μm birch peak in this zone is probably representative of the arboreal variety at a time of decreasing shrubs and establishment of trees. Engstrom and Hansen view this assemblage as a transformation of shrub-tundra to conifer forest. There is an associated decrease in the influx of willow, grasses, alder, and Ericales at both sites.

Macpherson's (1982) birch-spruce-balsam fir with poplar zone (8300-5400 BP) from the Avalon Peninsula also records an increase in arboreal pollen percentage to more than 60% (ours peaks to 45% in this zone), while shrub pollen decreases in percent and concentration. Effective precipitation was lower than at present, however, and openings created by fire would favour the growth of alder and shrub birch. Thus, while the major components of the modern boreal forest were now in place, the vegetation at both sites retained an understorey of shrubs and formed an open woodland assemblage.

Zone GI-5 *Alnus-Abies*-Poaceae (7600-6700 BP):

A dramatic charcoal peak at 7300 BP marks local fire that briefly altered the normal postglacial succession of vegetation on the Grey Islands, making this zone unique. The fire occurred during an 8000 to 6500 BP period of increased fire frequency on the Northern Peninsula (Macpherson, 1995). Following the fire, trees were partially replaced by shrubs and herbs, most notably alder and grasses.

The abundance of *Abies* before and after the fire suggests a forest in which fir was a more important component than it is in the modern spruce dominated boreal forest. Similar assemblages were observed by Lamb (1980) and Levac and de Vernal (1997) in the sequence leading to the development of the modern boreal forest in southeastern Labrador. Following the fire, both species are re-established, though *Abies* populations never again reach their previous frequencies. This may be partly due to black spruce's ability to maintain a fairly constant seed population that is not destroyed by fire, unlike that of fir (Dyer, 1986; Lamb, 1980). Spruce is also known to outcompete fir on recently burned sites (Jordan, 1975; Levac and de Vernal, 1997).

Zone GI-6 *Picea-Abies-Betula* (6700-5700):

This zone sees the closing of the boreal forest and establishment of the *Picea* dominated forest assemblage. Fir declines as it is outcompeted by spruce in marginal habitats. These include poor soils, sites that suffer from exposure, and probably most important at this site, recent disturbance by fire (Engstrom and Hansen, 1985; Jordan, 1975). There is a dramatic decrease in shrubs, especially alder and shrub birch, from the previous zone. The hypsithermal warm interval may be noted here in a decrease in shrubs and to a lesser extent herbs, combined with a closing of the boreal forest.

The closed crown boreal forest is composed primarily of spruce with patches of birch and fir. This assemblage is present in most of the studies discussed thus far:

Engstrom and Hansen (1985) 6000 BP; Lamb (1980) 6000 BP; Levac and de Vernal 1997) 6000 BP; Macpherson (1982) 5300 BP; and Vilks and Mudie (1983) 6500 BP. The continued presence of Cyperaceae in Lamb's (1980) southeast Labrador study is attributed to a lake-shore sedge community and may also explain the constant presence of Cyperaceae, even during optimal forest development, at the Grey Islands site.

Subzone GI-7a *Picea-Betula-Alnus* (5700-3500 BP):

Percentage, concentration, and influx are relatively steady through this zone, with high concentration and influx values that are indicative of closed crown boreal forest. There is a slight decrease in birch and corresponding increase in alder which has been cited by Davis (1983) as signalling the end of the hypsithermal, though this is usually accompanied by decreased influx which is not evident in the Grey Islands record. *Alnus, Myrica,* and *Coryloid* (probably degraded *Myrica*) increase in this zone, likely in conjunction with a post-hypsithermal opening of the forest due to a decrease in temperature, an increase in precipitation, or a combination of both (Anderson, 1980; Davis, 1983; Mott, 1975). *Sphagnum* also increases in this zone, however, and the increase in *Myrica*, a wetland plant that currently grows on the bog around the site, may correspond directly to this *Sphagnum* resurgence, thus being a purely site-specific occurrence.

Subzone GI-7b *Picea-Betula-Alnus*-shrubs (3500-1600 BP):

Total pollen influx declines dramatically at 2500 BP, corresponding to a large increase in *Sphagnum* and continued increase in shrubs. Ericales register a significant increase, interpreted by Engstrom and Hansen (1985) in their uppermost zone as the onset of a more open form of forest and possibly areas of lichen woodland. This change in vegetation probably registers the regional climatic deterioration and onset of paludification that is noted by Macpherson (1981), Davis (1984), and Davis *et al.* (1988).

Zone GI-8 *Alnus*-Cyperaceae-shrubs (1600-present):

Continuing deterioration and paludification are noted to present. All trees decline in their populations, while *Sphagnum* continues to increase. A slight increase in 20-25 µm birch grains at the top of the zone is probably an actual increase in shrub birch. Shrubs and herbs, especially alder, sedges, and Ericales, fill in the more open woodland vegetation. This trend is noted in studies around Newfoundland (Davis, 1984; Davis *et al.*, 1988; Macpherson, 1982 and 1997) and southeastern Labrador (Jordan, 1975; Levac and de Vernal, 1997; and Vilks and Mudie, 1983).

5.2 Regional Comparison

Following emergence from the postglacial Daly Sea, and until approximately 8700 BP, the Grey Islands vegetation was an open tundra community dominated by sedges, grasses, and other herbs, with dwarf willow as the dominant shrub. By 8400 BP, with the expansion of shrubs from existing populations (especially birch, *Alnus*, *Myrica*, and Ericales), a dwarf-shrub tundra vegetation was established. This occurs later at the Grey Islands site than in other parts of Newfoundland. Open tundra persisted throughout much of the island of Newfoundland until 11,000 BP, followed by shrub-dominated tundra communities which generally lasted until 10,000 BP in the southwest and more interior locations, 9600 BP in north central Newfoundland, and 8500 BP in the southeast (Anderson and Macpherson, 1994; Macpherson, 1995). Establishment of comparable communities in southeast Labrador, owing to proximity of the retreating ice and higher latitude, was delayed approximately 500 years behind the Grey Islands (Engstrom and Hansen, 1985; Jordan, 1975; Lamb, 1980; Levac and de Vernal, 1997).

Between 8400 and 7800 BP, as trees migrated in, the vegetation was evolving from a dwarf-shrub tundra to an open woodland with an understorey of shrubs. Spruce was established at approximately 7800 BP, followed 200 years later by balsam fir. Conifers arrived as much as 2000 years earlier at more interior parts of the island of Newfoundland (Macpherson, 1995) and were established by 9500 BP on the nearby Baie Verte Peninsula (Dyer, 1986). Arrival on the Northern Peninsula, however, was contemporary with the Grey Islands (Macpherson, 1995). In southeast Labrador there was again a 500 year delay (Jordan, 1975; Levac and de Vernal, 1997; Vilks and Mudie, 1983).

As the forest vegetation was becoming established, a local fire at 7300 BP altered the normal course of postglacial succession. Macpherson (1995) notes an increased occurrence of fire on the Northern Peninsula between 8000 and 6500 BP. A resurgence of alder and grasses at the expense of trees marks the 7600 to 6700 period on the Grey Islands.

After 6700 BP, a closed crown boreal forest dominated by spruce with patches of birch and fir, was established on the Grey Islands. This is contemporaneous with the Baie Verte Peninsula (Dyer, 1986) and coincides with a 6500 to 4000 BP period of forest development to or beyond its present limits (especially expansion of pine and black ash) in much of Newfoundland (Macpherson, 1995). The modern boreal forest was established in southeast Labrador at 6000 BP (Engstrom and Hansen, 1985; Jordan, 1975; Lamb, 1980; Levac and de Vernal, 1997; Vilks and Mudie, 1983).

After 4500 BP, the forest began to open with an increase in shrubs, especially alder, and a decrease in birch. This has been cited as signalling the end of the hypsithermal warm interval (Davis, 1983). This change is noted contemporaneously at other Northern Peninsula and north coastal sites (Macpherson, 1995), though the decline in birch and black ash is not definitively noted at the Baie Verte site until 3000 BP (Dyer, 1986). The forest limit on the Avalon Peninsula withdrew at 3500 BP (Macpherson, 1995).

The period around 2500 BP marks the onset of widespread paludification which dominates the remainder of the Grey Islands record. Total pollen influx declined dramatically, accompanied by a large increase in *Sphagnum*, shrubs, and herbs at the expense of trees. A more open form of forest, possibly with areas of lichen woodland, was established. This was a time of regional climatic deterioration, as noted at other Northern Peninsula and north coastal locations, though approximately 500 years later on the Baie Verte Peninsula (Davis, 1984, 1988; Dyer, 1986; Macpherson, 1995). More inland sites do not register the reduction in birch until 1500 BP (Macpherson, 1995). In Labrador the change is noted by 3000 BP (Engstrom and Hansen, 1985; Lamb, 1980; Vilks and Mudie, 1983).

The Grey Islands record generally corresponds to those of nearby Northern Peninsula sites. Migration of vegetation into the region followed its establishment at sites further south. The extreme maritime setting and higher latitude were probably both responsible for the late arrival of conifers at the Grey Islands. A similar delay is noted on the Northern Peninsula, and southeast Labrador lags even further behind. Climatic deterioration and onset of paludification are synchronous with nearby Northern Peninsula and north coastal locations, though the process began earlier in Labrador and lags by 1000 years at inland sites, suggesting the Labrador Current and ocean conditions as the probable forcing mechanism behind this change.

CHAPTER 6 CLIMATIC IMPLICATIONS OF THE POLLEN RECORD

6.1 Postglacial Environment of the Grey Islands

The rate of species migration and the composition of communities that occupied the Grey Islands over the last 9800 years are the result of complex interactions between climatic, oceanic, and biological factors. Postglacial climatic amelioration, suitable migration routes, availability of propagules, and soil maturity are all factors which shaped the development of vegetation on the Grey Islands. In addition to these controls, the site's proximity to the Labrador Sea offers a uniquely maritime perspective.

Following emergence from the postglacial Daly Sea at 9800 BP, an open herb-dominated tundra community colonized the area around the site and was gradually replaced by a low arctic dwarf shrub tundra. Tundra vegetation was present for 2000 years. The relatively long duration of this tundra phase is in agreement with Macpherson's (1995) observation of a slowing, or perhaps even reversal, of Newfoundland's postglacial warming trend between 9500 and 8500 BP. It was not until 8500 that temperatures and duration of the growing season began to increase consistently, permitting the rapid expansion of boreal forest trees (Macpherson, 1995). Edaphic conditions, specifically improved soil fertility through the nitrogen fixing abilities of abundantly growing alder, may also have aided in initial conifer invasion of the Grey Islands at 7800 BP (Lamb, 1980).

The ocean surrounding the island of Newfoundland remained dominated by arctic mollusc species until around 8000 BP, at which time there was a northward expansion of temperate taxa (Dyke *et al.*, 1996), suggesting a decrease in the cooling influence of the Labrador Current coincident with the arrival of conifer species on the Grey Islands. By 7000 BP Virginian mollusc species reach their maximum range extension in the northwest North Atlantic (Dyke *et al.*, 1996) and Levac and de Vernal (1997), in an examination of dinoflagellate cyst assemblages, report a significant warming (2-5° C) of sea surface conditions off of the Labrador coast. These indicators of an increasingly warm adjacent ocean environment coincide with the establishment of forest on the northernmost tip of the Northern Peninsula (Bell *et al.*, in press) and in southeastern Labrador (Engstrom and Hansen, 1984; Lamb, 1980; Levac and de Vernal, 1997; Vilks and Mudie, 1983). The thermal regime in the Labrador Sea appears to have had a profound effect on the postglacial timing and establishment of vegetation at its margins.

By 7800 BP, the influence of the cold Labrador Current was waning, propagules were available from adjacent Newfoundland to the south, and soil conditions were favourable to the establishment of boreal forest on the Grey Islands.

Between 7000 and 4500, an increase in tree birch in the Grey Islands record may be indicative of higher summer temperatures and a longer growing season. It is important to note, however, that this is also a period of increased fire frequency on the Northern Peninsula, a factor which Macpherson (1995) cites as permitting the expansion of tree birch at the expense of conifers and heathland plants. Yet, at the Grey Islands site, a local fire is accompanied by a large decrease in both conifers and birch with a corresponding increase in alder, followed by re-establishment of boreal forest. This might suggest that the increase in tree birch is indeed climatically controlled.

The period around 6000 BP may register the hypsithermal warm interval on the Grey Islands by a decrease in shrubs and herbs, combined with a closing of the boreal forest. A similar trend is noted on the Northern Peninsula at Stove Pond and Saddle Hill Pond (Bell *et al.*, in press; Macpherson, 1995), while chironomid evidence from Port au Choix reveals summers that were consistently warmer than today (Bell *et al.*, in press). This warmer interval is noted widely in other parts of Newfoundland and in southeastern Labrador (Bell *et al.*, in press; Dyer, 1986; Jordan, 1975; Levac and de Vernal, 1997; Macpherson, 1982, 1995). On Newfoundland's Baie Verte Peninsula, black ash extended its northeastern range beyond the modern limits, suggesting a lengthening of the growing season, while elevated balsam fir values at some sites on the north shore are indicative of increased winter temperatures (Macpherson, 1995). A rapid decrease in shrub birch with a corresponding increase in tree pollen is noted at an upland site on the Avalon Peninsula, while a lower site registers maximum arboreal pollen percentages, influx, and rate of sediment accumulation (Macpherson, 1982). In southeastern Labrador, many studies note closed crown boreal forest and full interglacial conditions after 6,000 BP (Engstrom and Hansen, 1984; Jordan, 1975; Lamb, 1980; Levac and de Vernal, 1997).

Regional climatic deterioration is observed in the records from sites around Newfoundland and southeastern Labrador after approximately 4000 BP. This is coincident with the increasing dominance of the cold Inner Labrador Current and establishment of modern sea surface conditions (Gajewski *et al.*, 2000; Levac and de Vernal, 1997). The island of Newfoundland generally experienced decreasing summer warmth, duration of the growing season, and importance of fire, while there was an increase in relative moisture. Primary indicators are an increase in shrubs and *Sphagnum* at the expense of trees, combined with decreased pollen influx and lacustrine productivity (Davis, 1984; Macpherson, 1981). This trend is registered earlier at northeastern and western coastal locations than inland, suggesting that a cooling of the ocean may indeed have lead the terrestrial deterioration (Macpherson, 1995). At the Grey Islands site, this period begins with a very slight decrease in arboreal birch, while shrubs and Sphagnum begin to register increases.

The most pronounced episode of paludification on the island of Newfoundland occurred from 3200 BP (Davis, 1984). Within this period falls the dramatic 2500 BP decline in total pollen influx at the Grey Islands site, accompanied by large increases in both *Sphagnum* and shrub populations as the boreal forest reverted to a more open woodland with associated areas of tuckamore and bog. On the western side of the Northern Peninsula, Stove Pond experienced an increase in herbs and small shrubs beginning at 4500 BP, followed by an increase in *Sphagnum* at the expense of conifers after 3500 BP (Macpherson, 1995). At Saddle Hill Pond to the north, a spruce decline was coupled with increases in alder and heath after 1000 BP, signifying an expansion of barrens at the expense of forest (Bell *et al.*, in press). Similar changes are noted at sites on the northeast coast after 3500 BP, in addition to the disappearance of black ash at Compass Pond and a sharp decline in pine at Leading Tickles (Dyer, 1986; Macpherson, 1995). In southeastern Labrador, an opening of the forest cover and the reappearance of certain shrub and herb components after 2500 BP are interpreted as a climatic shift to more severe conditions (Engstrom and Hansen, 1984; Lamb, 1980).

A regional summary of postglacial Holocene trends can be found in Table 6.1.

6.2 Marine Influence

A significantly warmer thermal regime was in effect in the Labrador Sea after approximately 7000 BP. This coincided with the establishment of closed crown boreal forest in northern Newfoundland and southeastern Labrador, which remained stable until the onset of climatic deterioration and paludification. The terrestrial cooling was probably driven by a return of the cold influence in surrounding ocean waters. Macpherson (1995) observed the decline in tree birch or pine at northeastern and western near-coastal sites 500 years prior to its registration inland. Since 2500 BP, the Inner Labrador Current has imposed colder bottom water temperatures than at any time since deglaciation (Scott *et al.*, 1984). This is registered on the Grey Islands and elsewhere in the region by an opening of the forest, resurgence of shrubs and herbs, and the onset of paludification.

6.3 Conclusions

Timing of initial forest development on the Grey Islands at approximately 7800 BP parallels development at other sites on the Northern Peninsula, is slightly earlier than in southeastern Labrador, and is as much as 1000 years later than the rest of Newfoundland. The timing is also coincident with a decrease in the cooling influence of the Labrador Current and a significant warming of sea surface conditions in the adjacent ocean. The hypsithermal warm interval is noted on the Grey Islands around 6000 BP during the interval of maximum sea surface temperatures in the Labrador Sea, and a climatic deterioration and paludification after 2500 BP coincide with the Labrador

Table 6.1 Regional Holocene Summary

Time (yrs BP)	Northern Peninsula			North Shore		Labrador		Offshore	Marine Records
	Grey Islands	Saddle Hill Pond	Stove Pond	Compass Pond	Leading Tickles	Southeastern Labrador	Lake Melville	Cartwright Saddle	NW North Atlantic
		Picea ↓ *Betula*+heath ↑							
1000	Forest ↓ Shrubs + herbs ↑								
2000	Wetland ↑			Barrens ↑ *Abies* ↑	*Picea* ↑ *Betula* ↓				
3000			Wetland ↑	*Fraxinus* ↓ *Picea* ↑ *Betula* ↓		Influx ↓			
4000	*Sphagnum* + shrubs ↑ *Betula* ↓	wetland ↑ *Alnus* ↑	Herbs-shrubs ↑ *Picea* ↑ *Betula* ↓		*Abies* ↓ *Pinus* ↓		Forest ↓ Sedge + grass ↑		
5000									Mollusc and Dinocyst assemblages indicate establishment of modern SSTs
6000	Shrubs +herbs ↓ Forest ↑	*Picea* ↑	Wetland ↑	Shrub birch ↓ *Fraxinus* ↑	*Pinus* ↑ *Abies* ↑		*Picea* ↑ *Abies* ↑ *Betula* ↑	*Picea* ↑	
7000	*Betula* ↑ *Abies* ↑	Shrub birch ↑ *Abies* ↑ *Picea* ↑	*Picea* ↓ *Betula* ↑ *Picea* ↑	*Betula* ↑	*Pinus* ↑	*Picea* ↑ *Abies* ↑	*Alnus* ↑	*Abies* ↑ *Picea* ↑	
8000	*Picea* ↑	Grass, sedge, heath	Emergence	*Picea* ↑	*Picea* ↑ *Abies* ↑	*Picea* ↑		*Alnus* ↑	Mollusc and Dinocyst assemblages indicate slight warming trend
9000		Emergence		*Alnus* ↑ *Abies* ↑ *Picea* ↑	*Picea* ↑		Sedges, shrubs	Herbs, dwarf shrubs	
10000	Herbs, shrubs Emergence (min. date)					*Alnus* ↑ *Betula* ↑			Mollusc and Dinocyst assemblages indicate harsh arctic conditions
11000				Sedges, shrubs		Herbs, dwarf shrubs			

↑ Increase ↓ Decrease Intensity of shading is relative to warming at particular site

Current's re-exertion of a cold bottom water influence. The results of this study suggest that the development and modification of vegetation on the Grey Islands is not only dependent upon atmospheric conditions and rates of species migration, but is also closely related to shifting thermal regimes in the surrounding ocean.

Even at a local scale there is evidence of the Labrador Current's effect on the islands. Mortsch *et al.* (1985) measured a southwest (warmer) to northeast (colder) temperature gradient around the Grey Islands which is visible in local vegetation. The sheltered western side of Bell Island supports surprisingly lush forest, while rock barrens and scrubby tuckamore predominate on the island's northeastern side which is closer to the Labrador Current and its cold ocean influence. There is also evidence of recent fire on the southwest side of Bell Island (confirmed in a telephone conversation with Mr. Earl Pilgrim, retired Wildlife Officer, Roddickton, 23 Jan. 2002: he states that the fire occurred about 1970).

Regionally, the Grey Islands record adds another perspective to those from the Northern Peninsula. The timing of vegetation development at a broad scale does not deviate significantly from other Northern Peninsula records. Establishment of shrub tundra, followed by boreal forest, occurs later than on the rest of the island, especially inland sites, and slightly earlier than in southeast Labrador. The hypsithermal warm interval is visible here and coincides with its registration in other regional records. Recent climatic deterioration, as noted in the aforementioned records, is concurrently recorded on the Grey Islands. This overview of postglacial vegetation on the Grey Islands provides a record that substantiates others from the adjacent Northern Peninsula and adds further validation to the reconstruction of Holocene palaeoclimate at the northern tip of Newfoundland.

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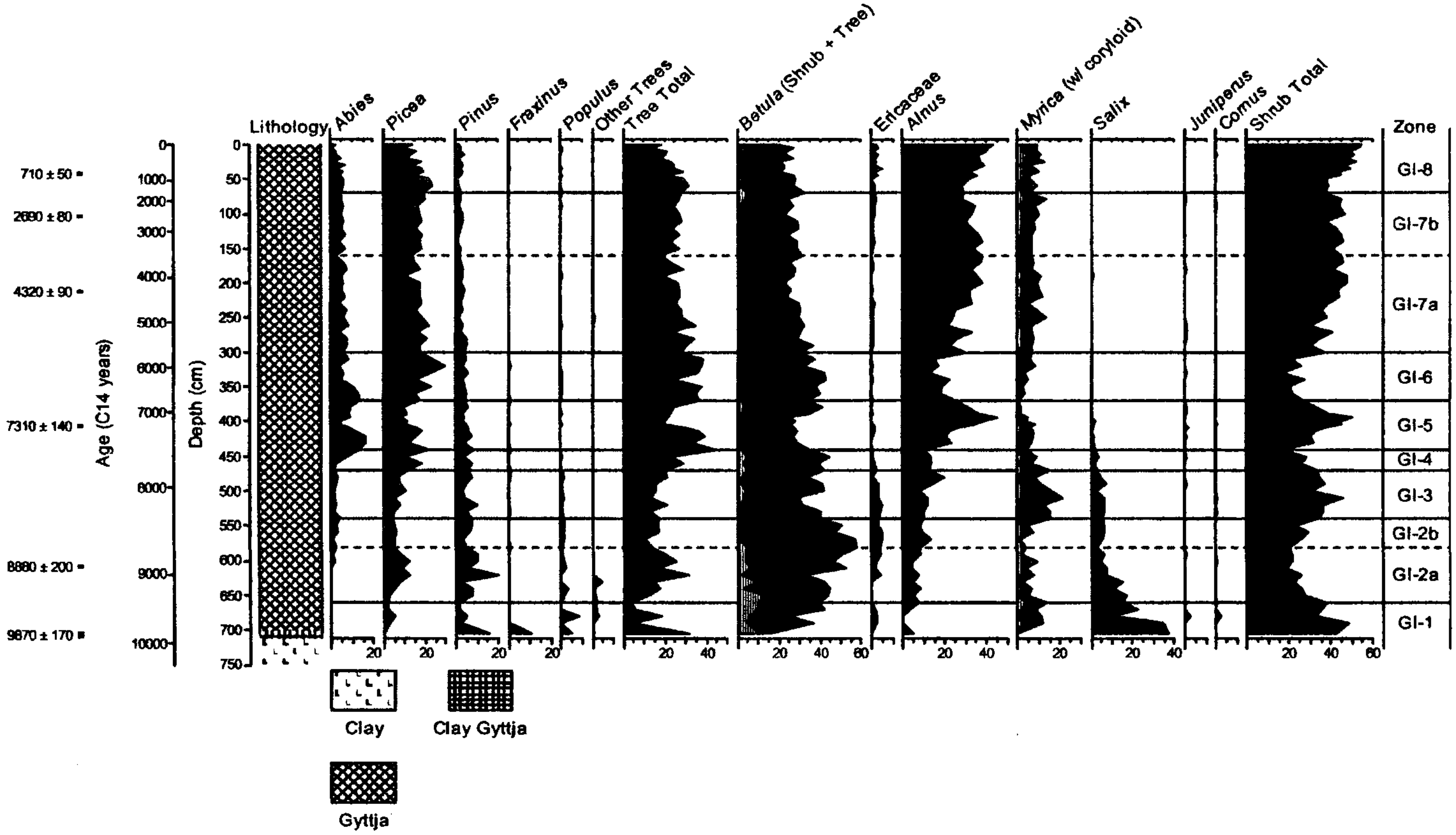

Figure A.1: Grey Islands pollen percentage diagram, trees and shrubs.

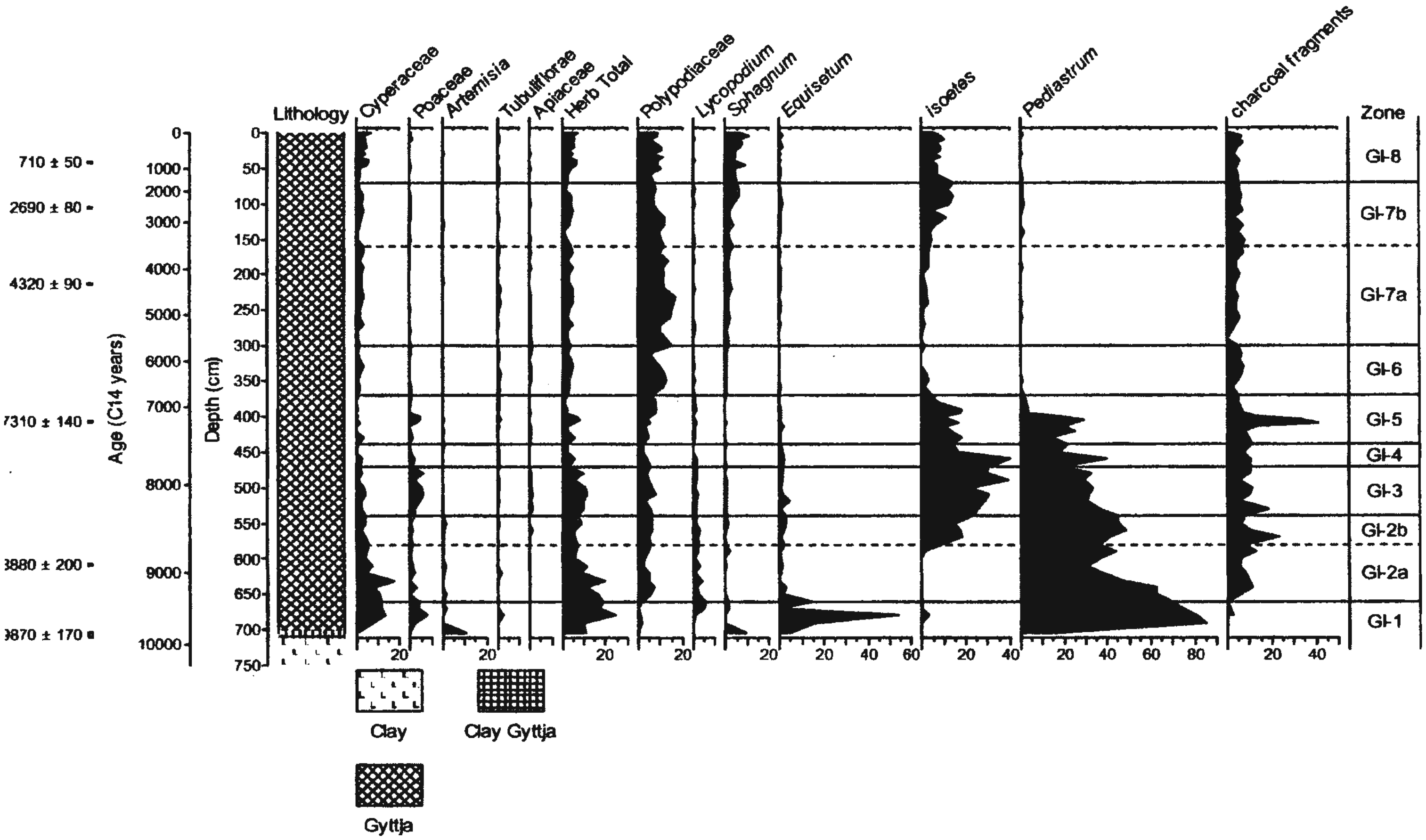

Figure A.1 (cont.): Grey Islands pollen percentage diagram, nonarboreal pollen.

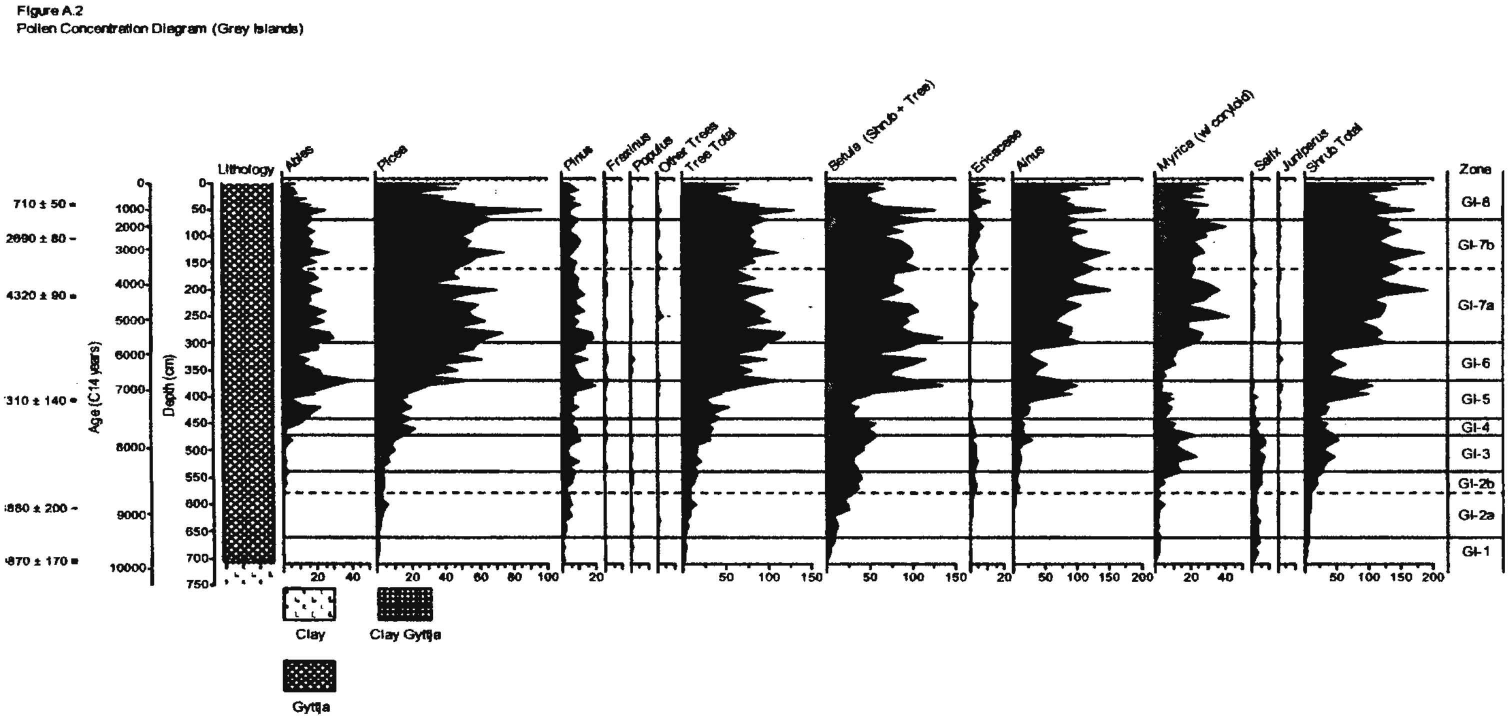

Figure A.2: Grey Islands pollen concentration diagram, trees and shrubs.

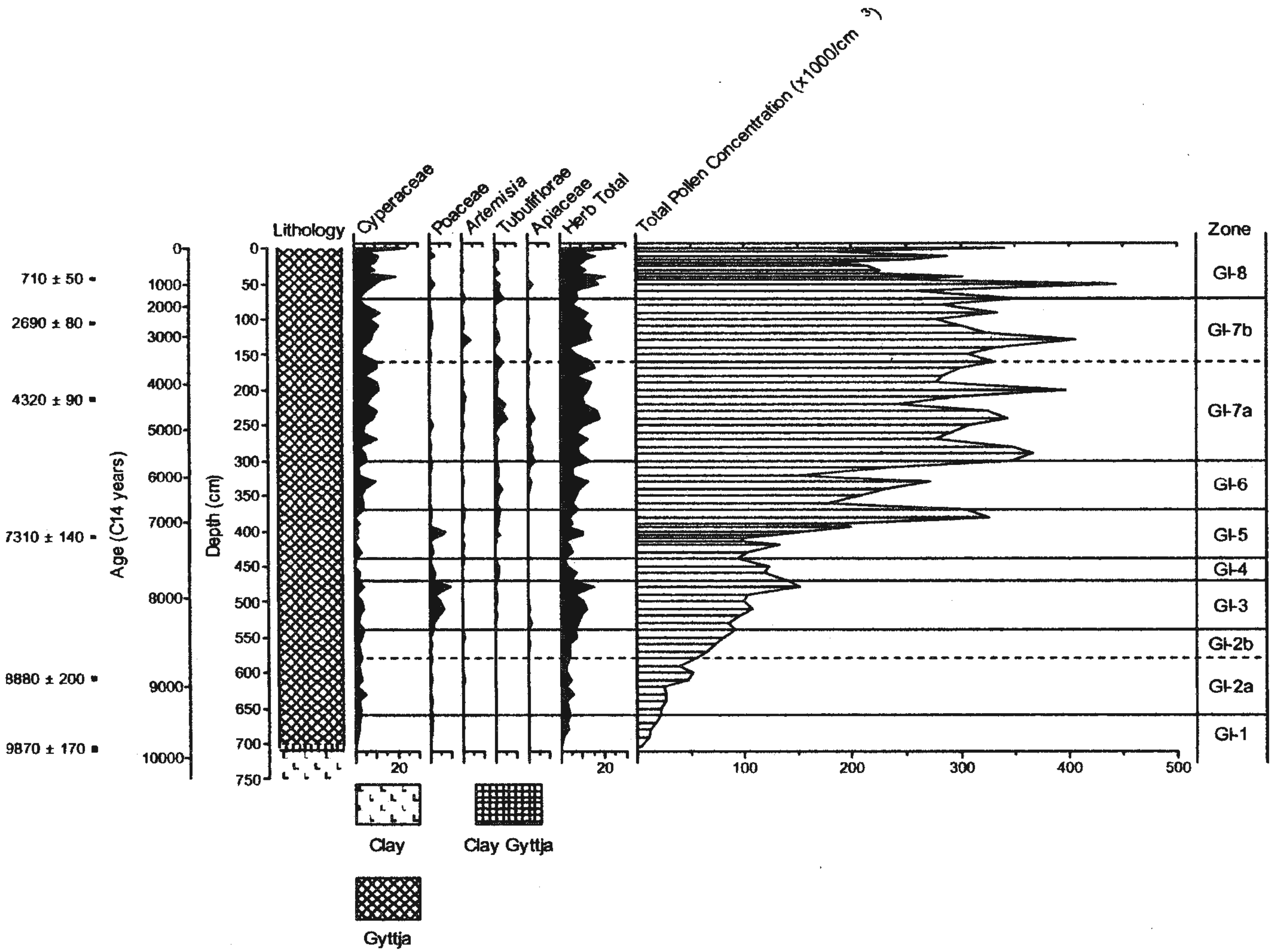

Figure A.2 (cont.): Grey Islands pollen concentration diagram, nonarboreal pollen and total pollen concentration.

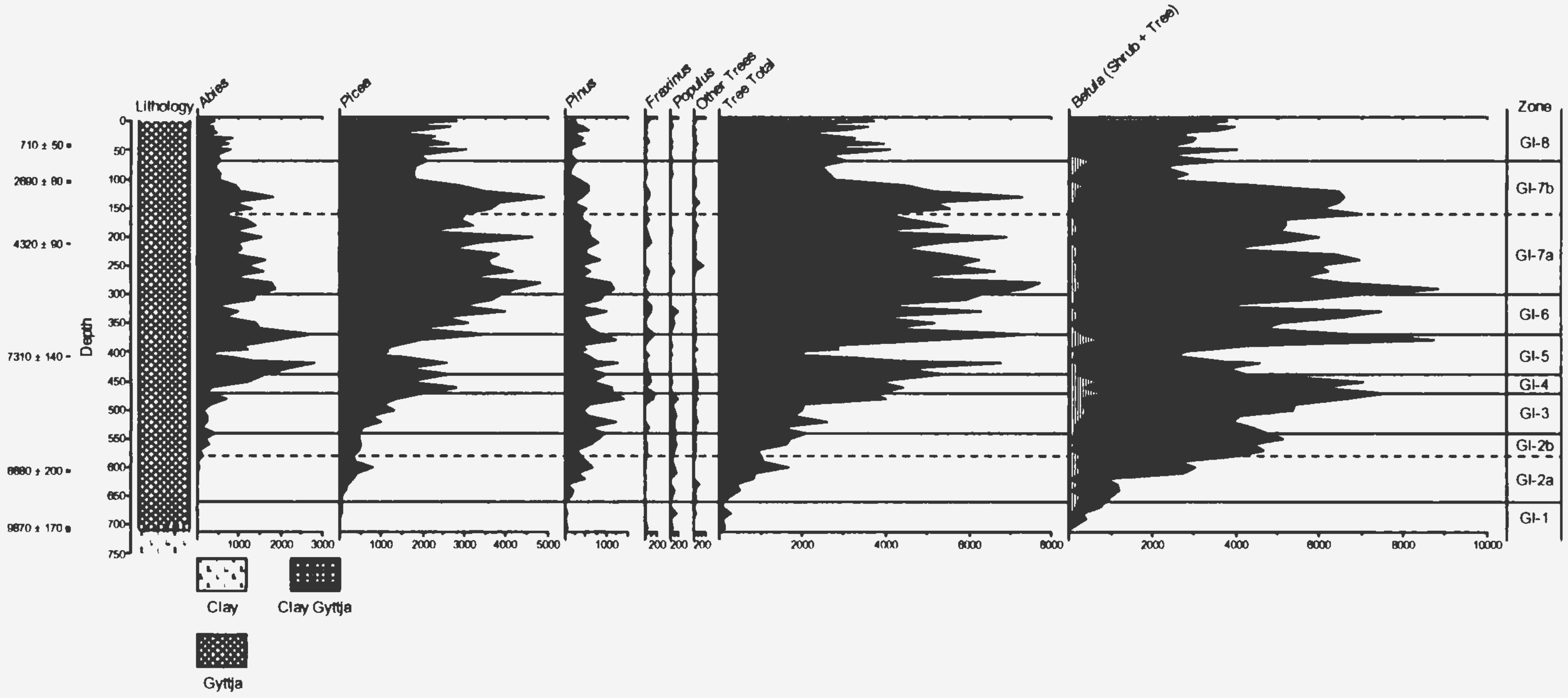

Figure A.3: Grey Islands pollen influx diagram, trees.

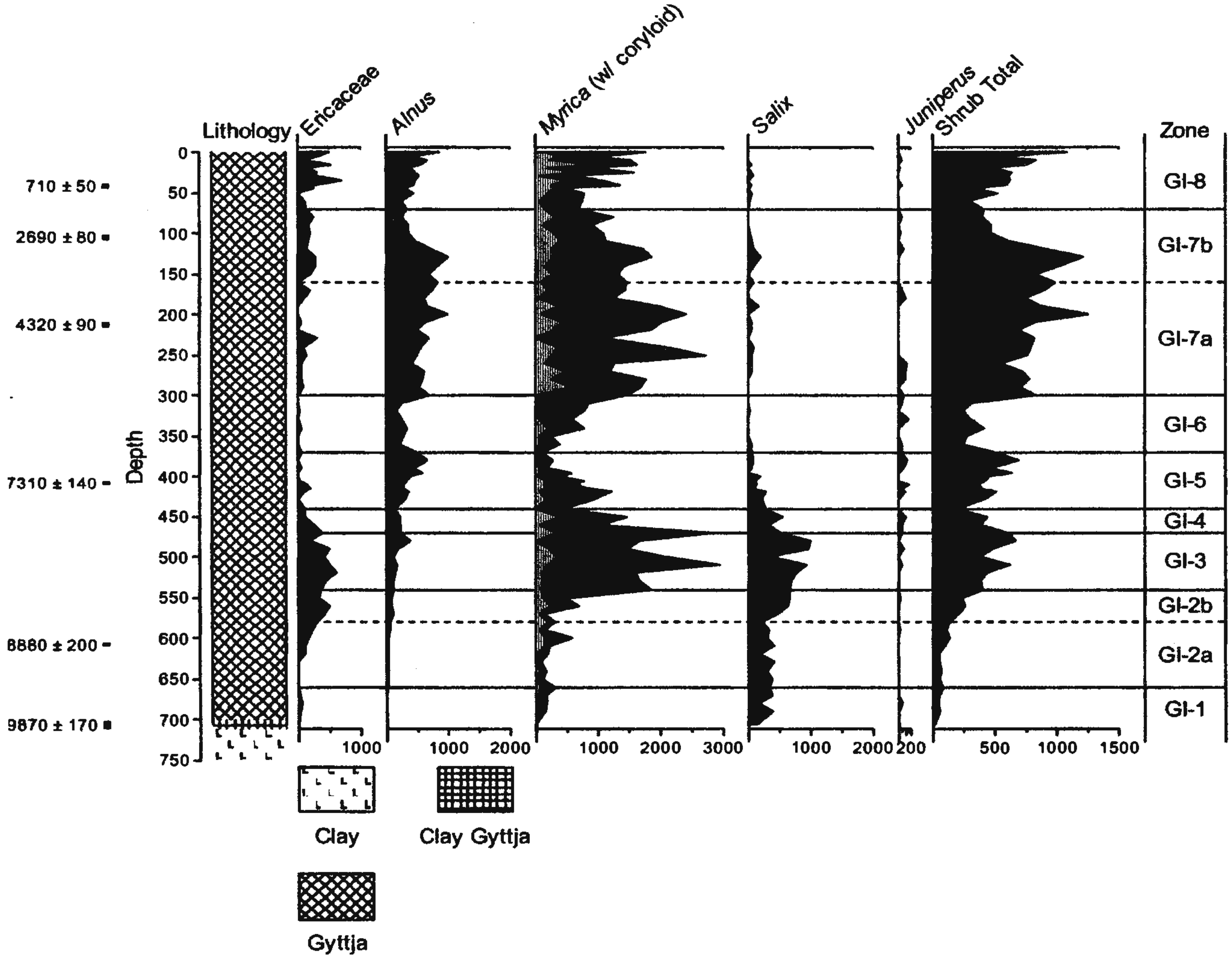

Figure A.3 (cont.): Grey Islands pollen influx diagram, shrubs.

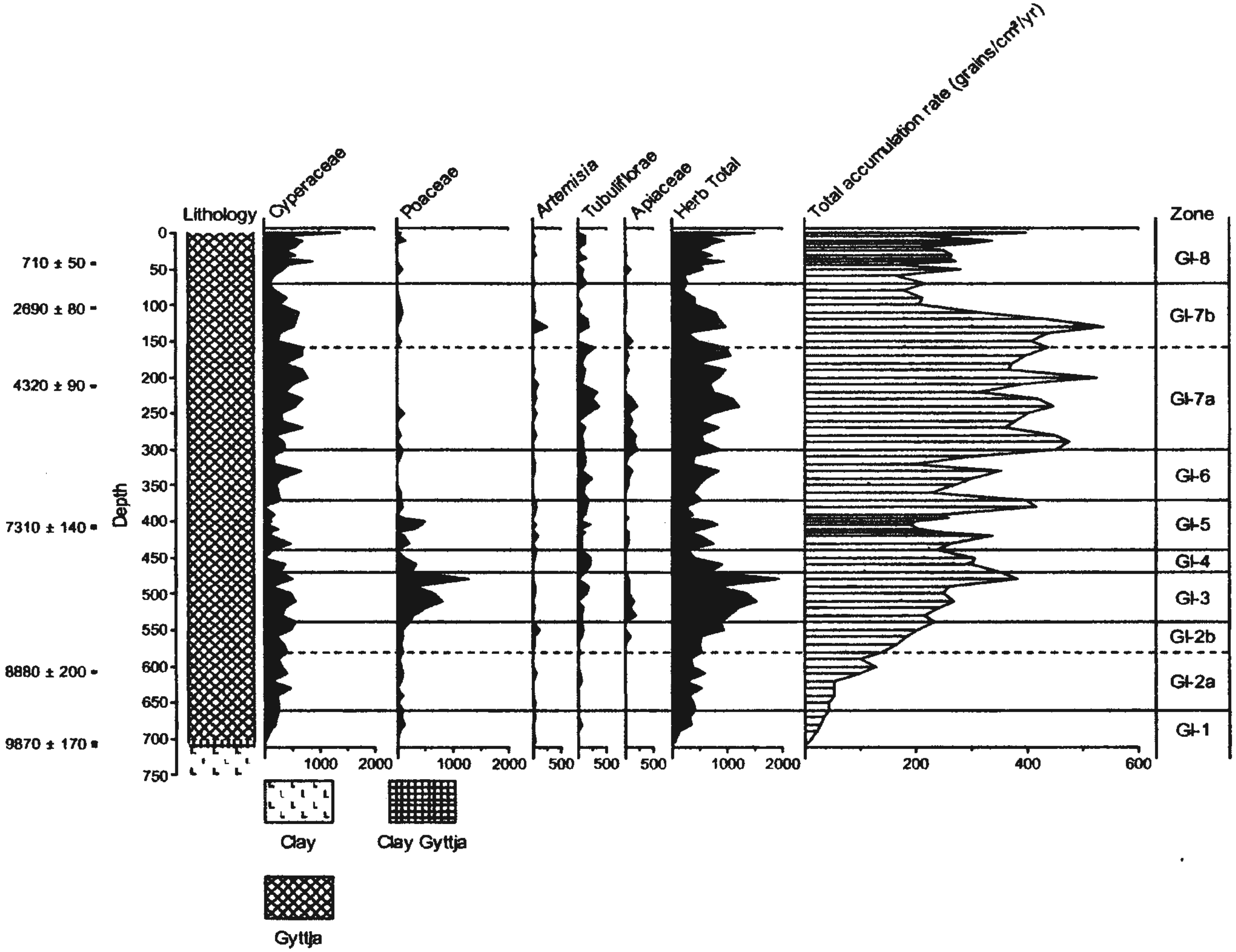

Figure A.3 (cont.): Grey Islands pollen influx diagram, nonarboreal pollen and total pollen influx.

Table A.1: Raw Fossil Pollen Counts

	0	5	10	15	20	25	30
exotic	102	197	122	123	197	168	173
Ab	7	3	7	7	15	4	23
Ac	0	0	0	0	0	0	1
Ct	0	0	0	0	0	0	0
Fg	0	0	0	0	0	0	0
Fr	1	0	1	0	1	0	1
Pc	45	29	51	38	36	60	51
Pn	4	9	8	11	5	9	12
Pp	0	1	1	0	0	0	0
Qu	1	0	0	0	1	0	0
Ts	1	0	0	0	0	0	0
Ul	0	0	0	1	0	1	0
BS	1	2	2	1	3	0	1
BL	1	0	1	0	7	0	6
BR	58	84	72	67	77	70	75
Cc	3	11	4	17	6	17	1
Er	8	9	2	10	6	8	7
Al	137	128	126	103	116	120	140
Cn	0	0	0	1	0	0	0
Jg	0	0	0	0	1	0	1
Ju	0	1	1	0	1	0	0
My	25	19	25	14	23	24	16
Os	0	0	1	1	0	0	0
Sl	0	0	0	1	0	1	2
Ap	0	0	0	0	0	0	1
Cp	0	0	0	0	0	0	0
CY	22	11	13	12	17	10	15
LG	1	0	0	0	0	0	0
PO	1	1	3	0	0	0	0
Ro	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0
TB	0	3	2	2	1	0	1
Ar	0	1	0	0	1	0	2
Ep	0	0	0	0	0	0	0
Pd	35	34	21	24	41	42	25
Eq	3	5	0	3	5	0	2
Ly	1	2	2	0	0	0	1
OS	0	1	0	0	0	0	0
Sp	27	45	24	26	29	19	20
IS	19	29	35	22	31	31	22
Mp	0	0	0	0	0	0	0
Nu	0	0	1	1	1	0	0
Np	1	2	1	2	1	0	3
Pm	3	2	1	1	1	0	2
ch	6	22	19	23	17	0	13
in	0	0	1	0	0	0	0
un	0	1	0	0	1	3	0

Table A.1 cont.

	35	40	45	50	60	70	80
exotic	149	120	139	87	139	77	120
Ab	8	18	11	20	19	12	15
Ac	0	0	0	0	1	0	0
Ct	1	0	0	2	0	1	0
Fg	0	0	0	0	0	0	0
Fr	2	1	0	1	1	1	0
Pc	56	63	46	76	76	47	63
Pn	7	12	9	4	6	7	7
Pp	1	0	1	0	0	1	0
Qu	0	2	0	0	0	0	0
Ts	0	0	0	1	0	0	0
Ul	0	0	0	0	0	0	0
BS	0	3	0	1	4	12	11
BL	0	0	0	5	3	0	0
BR	68	63	82	94	81	67	66
Cc	11	6	10	5	2	3	10
Er	16	6	9	0	4	3	8
Al	106	103	109	112	92	72	87
Cn	0	0	0	0	0	0	0
Jg	0	0	0	0	0	1	0
Ju	0	1	0	0	0	0	2
My	13	27	8	14	27	12	33
Os	0	0	1	0	0	0	0
Sl	0	1	0	1	1	0	0
Ap	0	0	0	2	0	0	0
Cp	0	0	1	0	0	0	0
CY	7	21	16	8	7	2	6
LG	0	1	1	0	0	0	0
PO	0	0	1	2	0	0	0
Ro	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0
Th	1	0	0	0	0	0	0
TB	3	0	0	2	2	3	0
Ar	0	0	0	0	0	1	0
Ep	0	0	0	0	0	0	0
Pd	40	33	35	43	22	20	28
Eq	0	2	0	4	2	0	1
Ly	1	2	0	0	1	0	2
OS	0	0	3	0	0	0	0
Sp	17	15	35	18	17	16	22
IS	29	17	23	26	25	41	43
Mp	1	0	0	0	0	0	0
Nu	2	1	0	0	0	2	1
Np	2	0	0	1	2	2	3
Pm	0	1	0	0	2	3	2
ch	n	19	14	14	17	n	17
in	0	0	0	0	0	0	0
un	1	0	3	0	1	0	0

Table A.1 cont.

	90	100	110	120	130	140	150
exotic	109	122	134	114	83	104	122
Ab	18	16	22	16	21	12	22
Ac	0	0	0	0	0	0	0
Ct	0	0	0	0	0	0	0
Fg	1	0	0	0	0	0	0
Fr	1	0	0	1	1	0	1
Pc	56	55	67	54	56	55	61
Pn	4	10	13	9	5	3	9
Pp	1	0	0	0	0	0	0
Qu	1	2	1	0	0	1	0
Ts	0	0	0	0	0	0	0
Ul	0	0	0	0	0	2	0
BS	4	1	8	3	2	2	1
BL	3	3	2	3	4	5	1
BR	82	66	95	95	69	85	98
Cc	3	8	9	4	3	2	4
Er	5	6	4	2	3	4	3
Al	113	102	109	111	112	120	115
Cn	1	0	0	0	0	0	0
Jg	0	1	0	0	0	0	0
Ju	0	1	0	1	0	0	0
My	25	24	17	23	18	18	18
Os	0	0	0	0	0	0	0
Sl	0	1	1	1	2	1	0
Ap	0	1	0	0	0	0	2
Cp	0	0	0	0	0	0	0
CY	12	8	14	9	6	4	4
LG	0	0	0	0	0	0	1
PO	1	1	2	1	0	0	1
Ro	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0
TB	0	1	0	2	2	0	0
Ar	0	1	1	0	3	0	0
Ep	0	0	0	0	0	0	0
Pd	29	26	36	49	44	35	43
Eq	1	4	1	1	1	1	0
Ly	2	2	1	0	1	1	3
OS	0	0	0	0	1	0	1
Sp	24	13	10	7	15	6	9
IS	56	46	18	43	20	12	17
Mp	2	0	1	1	0	0	0
Nu	0	0	0	0	2	0	2
Np	2	1	1	5	6	1	1
Pm	3	4	2	0	1	6	0
ch	22	18	29	11	25	16	30
in	0	0	0	0	0	0	0
un	1	0	0	1	0	0	0

Table A.1 cont.

	160	170	180	190	200	210	220
exotic	105	117	140	126	94	139	152
Ab	7	19	27	15	20	19	23
Ac	0	0	0	0	0	0	0
Ct	0	0	0	0	0	1	1
Fg	1	0	1	1	0	0	0
Fr	0	1	0	1	1	2	0
Pc	44	47	62	34	60	65	57
Pn	6	7	12	10	8	16	11
Pp	0	0	0	1	0	0	0
Qu	0	0	1	1	0	0	1
Ts	0	0	1	0	0	0	0
Ul	0	0	2	0	0	1	0
BS	1	2	3	4	1	2	5
BL	4	6	1	1	0	3	0
BR	96	75	96	82	76	94	73
Cc	1	3	1	6	1	8	6
Er	0	3	2	0	0	1	0
Al	120	119	117	114	129	119	106
Cn	0	0	0	0	0	0	0
Jg	0	0	0	0	1	0	0
Ju	0	1	2	0	0	0	0
My	20	20	23	28	30	31	33
Os	0	0	0	1	1	1	1
Sl	1	0	0	3	0	1	1
Ap	0	1	0	1	0	0	0
Cp	0	0	0	0	0	0	0
CY	10	11	7	12	10	10	8
LG	0	1	0	1	0	0	0
PO	0	0	0	0	0	0	0
Ro	0	0	0	0	0	0	0
Rb	0	1	0	0	0	0	0
Th	0	0	1	0	0	0	0
TB	4	2	1	2	1	1	7
Ar	0	0	0	1	0	2	1
Ep	0	0	0	0	0	0	0
Pd	46	37	58	41	47	48	50
Eq	0	1	0	1	1	2	4
Ly	3	1	5	1	0	0	3
OS	0	0	0	0	0	0	0
Sp	13	7	6	6	10	10	12
IS	11	9	12	9	1	4	7
Mp	0	1	1	0	0	0	0
Nu	1	0	0	1	0	0	1
Np	0	0	0	0	4	0	0
Pm	1	1	1	4	1	0	1
ch	20	24	14	12	19	14	11
in	0	0	1	0	0	0	0
un	1	1	0	1	1	0	1

Table A.1 cont.

	230	240	250	260	270	280	290
exotic	117	101	116	118	126	122	102
Ab	15	23	19	26	14	30	27
Ac	0	0	1	1	0	0	0
Ct	0	0	0	0	0	0	0
Fg	0	1	0	0	0	0	0
Fr	0	0	0	1	1	0	0
Pc	63	50	59	69	53	82	60
Pn	9	12	6	10	7	19	17
Pp	0	0	0	1	0	0	0
Qu	0	1	4	0	0	0	0
Ts	1	0	0	0	0	0	0
Ul	0	1	2	1	0	0	0
BS	4	2	4	3	3	5	4
BL	5	2	2	2	5	2	6
BR	95	94	91	97	90	105	116
Cc	0	5	4	2	8	4	8
Er	5	1	2	1	1	1	1
Al	112	79	78	68	104	100	76
Cn	0	0	0	0	0	0	0
Jg	0	0	0	0	0	0	0
Ju	0	0	0	2	2	2	0
My	18	25	40	19	13	26	16
Os	0	1	0	0	0	1	1
Sl	0	1	1	1	1	0	0
Ap	2	3	1	2	1	3	2
Cp	0	0	0	0	0	0	0
CY	11	8	5	5	12	3	5
LG	0	0	0	0	0	0	0
PO	0	0	2	0	0	1	0
Ro	0	0	0	0	0	0	0
Rb	0	1	0	0	0	0	0
Th	0	0	0	0	0	0	0
TB	4	5	3	0	2	1	1
Ar	1	0	1	0	0	1	0
Ep	0	0	0	0	0	0	0
Pd	74	61	60	56	40	41	53
Eq	0	1	1	0	2	0	0
Ly	0	2	0	0	3	3	1
OS	0	0	0	0	0	0	0
Sp	7	4	6	7	6	4	5
IS	8	9	1	1	3	2	0
Mp	0	0	0	0	1	0	0
Nu	1	0	1	0	0	0	0
Np	1	0	0	0	0	1	0
Pm	0	2	0	3	0	1	0
ch	16	14	14	17	n	8	0
in	0	0	0	1	0	0	0
un	0	0	0	1	6	0	0

Table A.1 cont.

	300	310	320	330	340	350	360
exotic	98	143	221	135	157	172	194
Ab	19	27	13	19	15	34	41
Ac	0	0	0	0	0	1	0
Ct	0	0	0	0	0	0	0
Fg	0	1	0	1	0	0	0
Fr	1	0	3	2	1	0	1
Pc	53	73	88	75	53	74	47
Pn	13	17	9	19	10	13	17
Pp	0	0	0	3	1	2	1
Qu	0	0	0	0	1	0	0
Ts	0	0	0	0	1	0	2
Ul	0	0	1	0	0	0	0
BS	2	4	2	3	6	2	3
BL	0	3	0	4	0	0	1
BR	94	108	96	134	137	120	121
Cc	0	0	0	1	4	1	1
Er	0	0	1	0	1	0	0
Al	93	46	51	44	74	62	56
Cn	0	0	0	0	0	0	0
Jg	0	0	0	0	0	0	0
Ju	1	1	0	3	0	0	1
My	20	17	24	10	13	5	9
Os	0	1	0	0	0	0	0
Sl	0	0	1	0	0	0	1
Ap	3	1	0	2	1	1	0
Cp	0	1	0	0	0	0	0
CY	5	3	6	12	7	5	7
LG	2	0	1	0	0	2	0
PO	1	1	0	0	0	0	1
Ro	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0
TB	1	2	3	1	5	3	2
Ar	0	0	1	1	0	0	0
Ep	0	0	0	0	0	0	0
Pd	56	18	24	35	45	49	39
Eq	0	0	0	0	0	0	1
Ly	1	0	1	2	0	2	0
OS	0	0	0	0	0	0	0
Sp	6	2	1	3	1	2	2
IS	4	0	0	0	8	11	3
Mp	1	0	0	0	1	0	1
Nu	1	0	2	2	1	2	0
Np	0	0	0	0	2	0	0
Pm	0	1	0	1	1	3	0
ch	15	20	18	25	21	15	7
in	0	0	0	0	0	0	0
un	0	0	0	1	1	1	0

Table A.1 cont.

	370	380	390	395	400	405	410
exotic	134	109	196	173	223	255	342
Ab	51	29	29	29	15	11	25
Ac	0	0	0	0	0	1	0
Ct	0	0	0	0	0	0	0
Fg	1	1	0	0	0	0	0
Fr	3	1	0	0	0	2	1
Pc	66	30	37	26	37	31	48
Pn	16	19	11	13	10	16	19
Pp	0	0	1	0	0	1	0
Qu	0	0	0	2	1	0	0
Ts	1	0	0	0	0	0	0
Ul	0	0	0	0	0	0	0
BS	6	12	8	1	8	4	4
BL	0	0	3	0	1	0	4
BR	121	121	107	80	80	75	78
Cc	0	0	1	1	1	5	4
Er	1	0	1	0	0	1	4
Al	92	99	121	142	122	105	84
Cn	0	0	0	0	0	2	0
Jg	1	0	0	0	1	0	0
Ju	1	2	2	0	0	0	5
My	2	4	4	13	12	19	15
Os	0	0	0	1	1	0	0
Sl	1	1	1	0	6	3	4
Ap	0	0	0	1	0	0	0
Cp	0	0	0	0	0	1	0
CY	5	0	5	2	4	2	7
LG	0	0	1	0	0	0	0
PO	1	1	0	2	15	13	9
Ro	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0
TB	3	2	3	1	2	6	1
Ar	1	1	1	0	0	2	0
Ep	0	0	0	0	0	0	0
Pd	27	30	30	29	18	13	19
Eq	0	0	1	2	2	3	3
Ly	3	2	6	4	0	4	5
OS	0	0	0	0	0	0	0
Sp	1	0	0	0	0	0	1
IS	17	26	77	69	37	46	66
Mp	1	0	1	0	0	0	0
Nu	2	2	1	0	0	0	0
Np	0	2	4	6	13	19	20
Pm	6	7	12	12	73	124	107
ch	19	15	n	25	49	155	222
in	3	0	0	4	0	2	1
un	1	0	0	1	1	2	1

Table A.1 cont.

	415	420	430	440	450	460	470
exotic	347	253	332	352	275	292	248
Ab	34	51	51	41	24	7	4
Ac	0	0	0	0	0	0	0
Ct	0	0	0	0	0	0	0
Fg	0	0	0	0	1	0	0
Fr	0	1	1	2	2	0	3
Pc	56	47	37	66	31	59	36
Pn	19	23	13	25	13	24	20
Pp	0	0	0	0	1	0	1
Qu	1	0	1	1	2	2	1
Ts	0	0	0	0	0	0	0
Ul	0	0	1	0	0	0	0
BS	2	3	5	5	15	8	15
BL	0	3	0	0	1	7	4
BR	88	77	85	102	123	109	115
Cc	3	1	4	0	7	1	6
Er	5	2	0	3	2	5	7
Al	68	62	74	30	43	44	40
Cn	0	0	0	0	0	0	0
Jg	1	0	0	0	0	2	1
Ju	1	2	0	0	2	1	1
My	19	21	18	12	22	21	44
Os	1	0	0	0	0	0	0
Sl	2	5	5	7	11	7	9
Ap	1	1	1	0	0	0	0
Cp	0	0	0	0	1	0	0
CY	2	2	11	4	0	8	5
LG	0	1	0	0	0	0	1
PO	0	2	5	0	2	7	4
Ro	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0
TB	3	1	1	1	4	4	2
Ar	1	2	0	2	1	0	0
Ep	0	0	0	0	0	0	0
Pd	12	12	15	8	7	14	20
Eq	7	2	2	3	4	7	5
Ly	3	2	3	1	1	5	6
OS	0	0	0	1	0	0	0
Sp	0	0	0	1	0	0	1
IS	40	49	75	51	61	215	146
Mp	0	0	1	0	1	0	0
Nu	0	1	0	0	0	0	0
Np	9	6	19	12	4	8	12
Pm	80	103	53	86	67	207	77
ch	50	26	33	38	25	36	36
in	0	1	0	1	0	0	1
un	2	1	0	2	2	2	0

Table A.1 cont.

	480	**490**	**500**	**510**	**520**	**530**	**540**
exotic	243	344	360	337	373	416	390
Ab	11	7	3	5	6	3	11
Ac	2	0	0	0	0	0	0
Ct	0	0	0	1	0	1	0
Fg	0	0	0	0	0	1	0
Fr	2	0	0	0	0	2	0
Pc	22	23	31	17	24	15	12
Pn	23	14	10	13	30	16	24
Pp	3	1	2	3	2	2	3
Qu	1	0	1	1	2	0	2
Ts	0	1	0	0	0	0	0
Ul	0	0	0	0	0	0	1
BS	5	7	10	8	5	4	4
BL	5	5	2	3	4	5	4
BR	95	110	115	80	87	110	114
Cc	0	4	8	4	2	3	2
Er	3	11	10	11	15	12	9
Al	60	42	26	37	35	29	30
Cn	0	0	0	1	0	1	0
Jg	0	0	0	1	0	0	0
Ju	0	2	0	1	0	0	0
My	27	29	41	61	37	42	45
Os	1	1	0	0	2	0	0
Sl	16	22	9	21	19	19	17
Ap	1	1	1	3	2	5	0
Cp	0	1	1	0	0	0	0
CY	8	3	11	12	9	8	14
LG	1	0	0	0	0	0	0
PO	20	7	15	18	13	7	5
Ro	0	0	0	0	0	0	0
Rb	0	0	0	0	2	5	2
Th	1	1	0	0	1	1	0
TB	0	4	3	0	2	1	1
Ar	0	1	1	0	1	0	0
Ep	0	0	0	1	0	1	0
Pd	13	17	21	28	11	19	22
Eq	4	4	3	6	17	2	10
Ly	7	6	4	8	7	6	7
OS	0	0	0	0	0	0	0
Sp	0	2	1	2	3	1	2
IS	131	202	86	133	125	103	92
Mp	0	0	0	1	0	3	0
Nu	0	0	0	0	0	0	0
Np	9	12	0	4	5	6	1
Pm	146	125	151	140	136	172	241
ch	36	18	37	36	18	66	26
in	0	1	0	1	0	0	0
un	0	2	2	1	1	0	0

Table A.1 cont.

	550	560	570	580	590	600	610
exotic	462	339	371	408	370	421	313
Ab	6	6	1	6	1	3	0
Ac	1	0	0	0	0	0	0
Ct	0	1	1	0	0	0	1
Fg	0	0	0	0	1	0	0
Fr	0	1	1	2	1	1	0
Pc	15	12	11	15	16	37	17
Pn	25	14	7	17	21	31	12
Pp	3	3	2	2	1	3	5
Qu	2	0	0	2	0	1	0
Ts	0	0	0	0	0	1	0
Ul	0	0	0	0	0	1	0
BS	1	3	2	13	8	11	13
BL	0	0	0	1	0	0	0
BR	155	94	112	163	95	130	95
Cc	3	5	1	8	2	6	5
Er	10	11	10	13	9	8	4
Al	27	19	27	27	16	16	9
Cn	0	0	0	0	0	1	0
Jg	0	0	0	0	0	0	0
Ju	1	0	0	0	1	0	0
My	12	10	2	5	3	21	3
Os	0	0	0	0	0	0	1
Sl	20	14	11	10	13	14	16
Ap	0	2	0	0	0	0	0
Cp	1	0	0	0	0	0	0
CY	14	5	8	18	10	14	16
LG	0	0	0	0	0	0	0
PO	2	2	1	4	1	2	3
Ro	0	0	0	0	0	0	0
Rb	3	0	1	0	0	1	0
Th	2	1	0	0	1	0	0
TB	2	1	0	1	0	0	1
Ar	4	1	1	0	1	0	3
Ep	0	0	1	0	0	0	0
Pd	22	16	11	20	11	9	5
Eq	12	6	2	7	2	2	3
Ly	6	7	5	10	6	2	7
OS	0	0	0	0	0	0	0
Sp	4	1	0	3	5	0	2
IS	56	46	48	32	3	0	0
Mp	1	0	0	0	0	0	1
Nu	0	0	0	0	0	0	0
Np	9	7	12	42	6	14	5
Pm	254	196	139	179	156	177	92
ch	20	23	62	26	30	21	12
in	1	0	0	0	0	0	0
un	0	0	0	0	0	1	0

Table A.1 cont.

	620	630	640	650	660	670	680
exotic	274	108	171	211	177	245	201
Ab	0	0	0	0	0	0	0
Ac	0	0	0	0	0	0	0
Ct	0	0	0	1	1	0	1
Fg	0	0	0	0	0	1	0
Fr	0	0	0	0	0	0	0
Pc	12	3	3	2	1	1	2
Pn	19	1	5	5	1	1	2
Pp	0	0	2	1	0	0	3
Qu	0	2	0	0	0	0	0
Ts	0	0	1	0	0	0	0
Ul	0	0	0	0	0	0	0
BS	2	4	2	8	5	6	2
BL	0	0	0	0	0	0	0
BR	30	13	26	21	16	19	7
Cc	1	0	1	0	2	1	0
Er	4	0	0	0	0	1	1
Al	7	2	5	3	4	2	0
Cn	0	0	0	0	0	0	1
Jg	0	0	0	0	0	0	0
Ju	0	0	0	0	0	0	1
My	6	1	3	3	5	4	4
Os	0	0	0	0	0	0	0
Sl	7	6	7	11	8	13	4
Ap	0	0	0	0	0	0	0
Cp	0	1	0	1	0	0	0
CY	4	7	5	7	6	7	5
LG	0	0	0	0	0	0	0
PO	2	0	2	0	2	2	3
Ro	0	0	0	2	0	0	0
Rb	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0
TB	2	0	0	0	0	0	1
Ar	1	0	0	1	0	1	0
Ep	0	0	0	0	1	0	0
Pd	5	2	5	4	1	0	1
Eq	1	0	2	1	11	0	46
Ly	1	2	1	2	4	3	1
OS	0	0	0	0	0	0	0
Sp	0	0	0	0	1	1	0
IS	0	0	0	0	0	0	1
Mp	0	0	0	0	0	0	0
Nu	0	0	0	0	0	0	0
Np	11	14	2	0	1	0	0
Pm	58	35	103	108	121	176	149
ch	8	n	8	n	0	n	1
In	0	0	1	0	0	0	0
un	0	2	1	0	0	1	1

Table A.1 cont.

	690	705
exotic	268	308
Ab	0	0
Ac	0	0
Ct	0	0
Fg	0	0
Fr	0	2
Pc	1	0
Pn	1	3
Pp	0	1
Qu	0	0
Ts	0	0
Ul	0	0
BS	2	2
BL	0	0
BR	13	1
Cc	1	0
Er	1	0
Al	0	1
Cn	0	0
Jg	0	0
Ju	0	0
My	4	0
Os	0	0
Sl	14	7
Ap	0	0
Cp	0	0
CY	3	0
LG	0	0
PO	1	0
Ro	0	0
Rb	0	0
Th	0	0
TB	0	0
Ar	0	2
Ep	0	0
Pd	1	0
Eq	8	1
Ly	0	0
OS	0	0
Sp	0	2
IS	0	0
Mp	0	0
Nu	0	0
Np	4	0
Pm	233	4
ch	n	n
in	0	0
un	0	1

Key to Table A.1

Ab	*Abies*
Ac	*Acer*
Ct	*Castanea*
Fg	*Fagus*
Fr	*Fraxinus*
Pc	*Picea*
Pn	*Pinus*
Pp	*Populus*
Qu	*Quercus*
Ts	*Tsuga*
Ul	*Ulmus*
BS	*Betula* (<20 μm)
BL	*Betula* (>25 μm)
BR	*Betula* (20-25 μm)
Cc	Coryloid
Er	Ericaceae
Al	*Alnus*
Cn	*Cornus*
Jg	*Juglans*
Ju	*Juniperus*
My	*Myrica*
Os	*Ostrya*
Sl	*Salix*
Ap	Apiaceae
Cp	Chenopodiaceae
CY	Cyperaceae
LG	Liguliflorae
PO	Poaceae
Ro	Rosaceae
Rb	Rubiaceae
Th	Thalictraceae
TB	Tubuliflorae
Ar	*Artemisia*
Ep	*Epilobium*
Pd	Polypodiaceae
Eq	*Equisetum*
Ly	*Lycopodium*
OS	*Osmunda*
Sp	*Sphagnum*
IS	*Isoetes*
Mp	*Myriophyllum*
Nu	*Nuphar*
Np	*Nymphaea*
Pm	*Pediastrum*
ch	Charcoal fragments
in	Indeterminate
un	Unknown