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Environmental change in the Great Whale River region, Hudson Bay: Five decades of multidisciplinary research by Centre d'études nordiques (CEN)[1]

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Abstract: The Great Whale River region on the eastern shore of Hudson Bay, Canada, encompasses the villages of Whapmagoostui (Cree First Nation) and Kuujjuarapik (Inuit) and surrounding areas. The principal field station of Centre d'études nordiques (CEN: Centre for Northern Studies) has operated at Whapmagoostui-Kuujjuarapik (W-K; 55° 15' N, 77° 45' W) since the 1970s, with diverse research projects on past and present environments. The climate at W-K is strongly influenced by the proximity of Hudson Bay, and the recent pronounced loss of sea ice in this sector of northern Canada has been accompanied by large increases in air temperature. Discontinuous or scattered permafrost occurs throughout the region and is degrading rapidly. The W-K region continues to experience particularly rapid isostatic uplift in response to the retreat of the Laurentide Ice Sheet. Parabolic dunes occur along the coast and are strongly influenced by the plant cover. Paleoecological studies have documented the Holocene evolution of landscapes, including lakes, wetlands, and forests. The vegetation type is coastal forest tundra, with some 400 recorded species. Studies on certain insect groups provide a baseline for assessing future ecological change. The first signs of human occupation in the W-K region have been dated at 3800 BP. The arrival of the Hudson's Bay Company in the 18th century marked the onset of continuous occupation. Rapid social, economic, and environmental change initiated in the mid-20th century continues to this day.
Keywords: climate change, cryosphere, forest tundra, Hudson Bay, isostatic uplift, landscape, Subarctic.

Résumé : La région de la Grande rivière de la Baleine, sur la côte est de la baie d'Hudson, Canada, comprend les villages Cri (Whapmagoostui) et Inuit (Kuujjuarapik), ainsi que les zones environnantes. Le Centre d'études nordiques (CEN) opère à Whapmagoostui-Kuujjuarapik (W-K : 55° 15' N, 77° 45' O) sa principale station de recherche depuis la décennie 1970. De nombreuses recherches portant sur l'étude des environnements passés et actuels y ont été menées. Le climat de la région est fortement influencé par la proximité de la baie d'Hudson où, depuis quelques décennies, la diminution de la glace de mer a été accompagnée d'une augmentation significative de la température de l'air. Le pergélisol est discontinu ou dispersé et présentement en dégradation. La région est caractérisée par un taux de relèvement isostatique particulièrement rapide en réponse au retrait de l'Inlandsis laurentidien. Des dunes paraboliques, situées le long de la côte, progressent en étroite relation avec le couvert végétal. Des études paléoécologiques ont documenté l'évolution holocène des paysages incluant les lacs, les zones humides et la forêt. La région de W-K est située dans la zone littorale de la toundra forestière. Sa flore, de type subarctique, comporte quelque 400 espèces recensées. Des études ciblées sur des groupes d'insectes spécifiques fournissent une base pour évaluer les changements écologiques futurs. Les premiers signes d'occupation humaine dans la région de W-K ont été datés à 3800 ans BP. L'arrivée de la Compagnie de la Baie d'Hudson au 18e siècle a marqué le début d'une occupation continue du territoire. Des changements sociaux, économiques et environnementaux rapides amorcés au milieu du 20e siècle se poursuivent encore aujourd'hui.
Mots-clés : Baie d'Hudson, changements climatiques, cryosphère, paysage, relèvement isostatique, subarctique, toundra forestière.

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Introduction

High-latitude regions of the Northern Hemisphere are experiencing rapid climate change, and considerable attention is now focused on the effects on north polar geosystems and ecosystems. Climate models and observations imply that the fastest warming rates in the lower atmosphere are occurring at latitudes from 75° N to the North Pole (Screen & Simmonds, 2010). Although this has underscored the need to continue monitoring changes in the extreme High Arctic (Vincent *et al.*, 2011), there are other regions of the circumpolar North that are also experiencing large shifts in climate, accompanied by impacts on landscapes, vegetation, and wildlife. One such area is the eastern Hudson Bay region of subarctic Quebec, Canada, where the climate, permafrost, and many biological communities appear to be in a state of rapid transition (Payette *et al.*, 2004).

The Centre d'études nordiques (CEN: Centre for Northern Studies) began studies in the Great Whale River area, southeastern Hudson Bay, in the 1960s based out of Whapmagoostui-Kuujjuarapik (W-K; 55° 17' N, 77° 47' W), at the mouth of the Great Whale River (Figures 1 and 2). In 1968 CEN began to develop a research station in the village of W-K, on the site where it had inherited buildings from the Quebec government. Over the years, this became the principal site for the CEN Network of field stations (Qaujisarvik, meaning "place of study" in Inuktitut), which extends over 3500 km from Radisson (53° 47' N, 77° 37' W) in the James Bay region to Ward Hunt Island (83° 6' N, 74° 10' W) at the northern tip of North America, and which since 2009 has been part of SCANNET, the circumpolar network of terrestrial field stations. The W-K station was established in the early seventies in the wake of the early development of "Hudsonie", the CEN's multidisciplinary research project in 1968-1969 (Hamelin & Cailleux, 1968). The aim of this project was to collect preliminary geomorphological, climatological, and ecological data. Since then, CEN research has not only intensified, but has also greatly broadened its research on the region's geosystems and ecosystems, with emphasis on environmental change in the past and present. Our aim is that this review article, written in commemoration of the 50th anniversary of the founding of CEN, will serve as an introduction to the subarctic Great Whale River region, and that it will provide a basis for comparisons with other sites in the fast changing North.

Great Whale River region

The region covered by this article includes the adjacent Cree (Whapmagoostui; "place of the beluga" in Cree) and Inuit (Kuujjuarapik; "little great river" in Inuktitut) villages that host CEN's research station and the surrounding area. We include in this region the area within 50 km north, 10 km south, and 15 km east of W-K (bounded to the west by the sea) to encompass the full range of environmental studies by CEN researchers based out of the W-K station. The region is located on the southeastern part of Hudson Bay (Figure 1) and encompasses an area of about 900 km^2, including the Manitounuk Islands and Manitounuk Strait. The region is underlain by discontinuous, scattered permafrost (Allard & Seguin, 1987) in the forest subzone of the forest tundra zone (Payette, 1983).

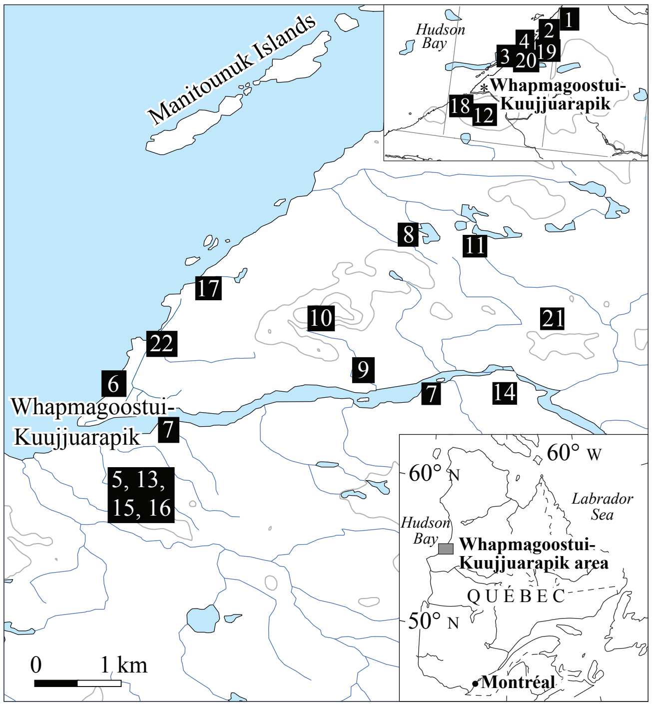

FIGURE 1. Location of the Great Whale River region and sites mentioned in the text.

The Great Whale River (Grande rivière de la Baleine in French) flows 724 km, from Lake Saint-Luson, through Lake Bienville, to the sea at W-K (Figure 2a). With a drainage basin of 42 735 km^2, it is one of the most important rivers of northern Quebec, achieving peak flows of around 1740 m^3·s^{-1} in late May (Déry *et al.*, 2005) and an annual average discharge of 700 m^3·s^{-1} (Grainger, 1988). Its influence also extends well into the sea, exporting organic carbon and nutrients (Hudon *et al.*, 1996; Retamal *et al.*, 2007) and producing a freshwater plume that extends offshore over an area of about 100 km^2 of coastal Hudson Bay in summer and autumn, increasing up to 1000 km^2 in February and 2000 km^2 in March (Ingram, 1981). The Great Whale River and its freshwater plume have been studied by researchers based out of the CEN Station at W-K, but a full account of these and related studies on the coastal marine ecosystem that it discharges into is outside the scope of the present review. The W-K area also contains numerous lakes that have been the subject of limnological research that is still ongoing (*e.g.*, Rae & Vincent, 1998; Swadling *et al.*, 2001; Rautio & Vincent, 2006; Laurion *et al.*, 2010; Watanabe *et al.*, 2011; see also Rautio *et al.*, 2011) and paleolimnological studies (reviewed below).

Climate and snow conditions

The subarctic climate of the W-K region was described in detail by Wilson (1968) for the period 1932 to 1960, and a compilation of subsequent data from 1961 to 2000 is provided by Environment Canada (2010). Climate normals for these periods were similar. Mean annual temperatures

Figure 2. a) Whapmagoostui-Kuujjuarapik on the Great Whale River, subarctic Quebec, Canada. The sea is on the left (Strait of Manitounuk, Hudson Bay) and the river is on the right. b) Old-growth forest located in the Cri Valley. c) Sasapimakwananisikw palsa bog, located 8 km south of the village. d) Lake Kachishayoot, located about 3 km inland from the eastern shore of Hudson Bay on granite-gneiss rocks of the Precambrian Canadian Shield. e) Cree campsite located in the spruce–lichen on the south bank of the Great Whale River. f) Manitounuk Islands viewed from the coast.

were –4.2 °C for 1932–1960, –4.5 °C for 1961–1990, and –4.4 °C for 1971–2000. However, mean annual temperatures have been considerably higher over the last decade (2000–2010), and negative temperature anomalies (*i.e.*, mean annual temperatures less than the 20th century average for W-K) are now rarely observed (Figure 3). Mean annual air temperatures for the period 2001–2010 averaged –2.6 ± 1.2 °C, significantly above that for 1960–2000 (–4.3 ± 1.6 °C; $t = 3.78$, $P < 0.001$). January has always been the coldest month, with mean temperatures of –22.8 °C (1932–1960) and –23.4 °C (1961–2000), and August has been the warmest, with respective means of 10.6 and 11.4 °C. Mean annual precipitation was 680 and 656 mm, respectively, 40% of which fell as snow (Wilson, 1968; Environment Canada, 2010). Average wind speed is 5.6 $m·s^{-1}$ (1932–2000). Wind direction varies seasonally; winds are predominantly easterly and south-easterly in autumn and winter but northerly in the spring and summer. Average monthly wind speeds are greatest from September to December, during which time the strongest winds are usually associated with the passage of atmospheric lows. The wind has a major effect on the distribution pattern and compaction of the snow cover and on the distribution of permafrost and vegetation.

The climate at W-K is greatly influenced by the proximity of Hudson Bay, more specifically by the extent of ice cover (Wilson, 1968). Once the bay freezes up, usually from January to May, the area's climate becomes continental, with cold temperatures, low precipitation, and reduced cloudiness. In summer and fall, the climate reverts to the maritime type, and sunshine is greatly reduced, chiefly due to the frequent dense fogs, particularly along the coast (Plamondon-Bouchard, 1975). As in all northern regions, snow is a major ecological and geomorphological factor. In winter, the snow fills depressions and valleys and thereby produces a more even topography. The region's snow cover dynamics were studied by Payette and Lagarec (1972), Filion (1976), and Filion and Payette (1976; 1978). The thickness of the snow cover varies depending on the proximity of the shore, the relief of the land, and the broader structural types of the local vegetation. The coastal area retains the least snow, as it is most exposed to the prevailing winds coming off the bay. The snowiest sites are the depressions, steep slopes, and deep bedrock fractures. These relief types are also characterized by early snow cover and late snow thaw. In forested sites, the thickness and density of the snow cover increase with altitude. In exposed sites dominated by low-growing vegetation, the snow cover thickness may vary, although its density is uniform and generally high (Filion & Payette, 1976). In forested stands, snow and sunlight are intercepted by the canopy, resulting in lower soil temperatures than at open sites (Filion & Payette, 1978).

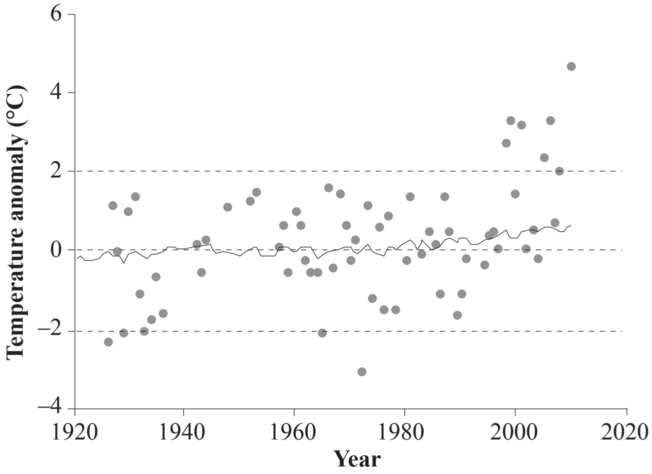

FIGURE 3. The air temperature anomaly (deviation from the 20th century mean value) for Kuujjuarapik. The data are from Environment Canada (circles), and the full line gives the mean global anomaly (http://data.giss.nasa.gov/gistemp/tabledata/GLB.Ts.txt).

Sea ice conditions in Hudson Bay have been changing rapidly over the last decade, and the climate of W-K is undergoing shifts that are without precedent for at least 90 y, and perhaps much longer. A compilation of remote sensing data from the Canadian Ice Service archives shows that sea ice decline in Hudson Bay has been faster than in any other Canadian Arctic region, decreasing at an average rate of 11.3 ± 2.6% per decade between 1968 and 2008 (Tivy *et al.*, 2011). These declines have continued; in January 2011, open water conditions were observed in Manitounuk Strait (C. Tremblay, CEN station manager, pers. comm.). This dramatic > 40% overall decline in sea ice coverage has been accompanied by unusually high air temperatures. For the most recent annual record (2010), the temperature anomaly at this Environment Canada station was more than 7 times the global average (Figure 3).

Permafrost and periglacial processes

Permafrost is an important factor in northern landscapes. The W-K region is located in the discontinuous, scattered permafrost area and lies in zone C of the northern Quebec permafrost distribution map (Figure 4a, Allard & Seguin, 1987; Payette, 2001). In this region, permafrost occupies much less than 50% of the land surface and is principally concentrated on barren hilltops. In certain areas, permafrost may be as much as 100 m thick (Botteron *et al.*, 1979).

More specifically, the W-K region is in sub-sector C^1, which was described by Allard and Seguin (1987) as an area characterized by palsas overlying fine Tyrrell Sea sediments and by scattered permafrost under exposed bedrock hills in the wind-blown rocky hills along the coast. The earliest research work on the region's permafrost dates back to 1969. Some palsas in a peat bog 8 km south of W-K (Figure 2c) were described by Hamelin and Cailleux (1969), and later by Botteron *et al.* (1979). Rocky mounds of periglacial origin (later referred to as heaved bedrock features; Dionne, 1984) were also observed in certain areas of subarctic Quebec, notably in the basaltic bedrock of the Manitounuk Islands. These mounds were characterized as belonging to 3 morphological types: crevassed blocky mounds, centrally or peripherally blocky mounds, and gelifract-covered mounds (Payette, 1978). These forms owe their shape to the build-up of hydraulic pressures in the active layer of the bedrock and to gelifraction (Michaud & Dionne, 1987).

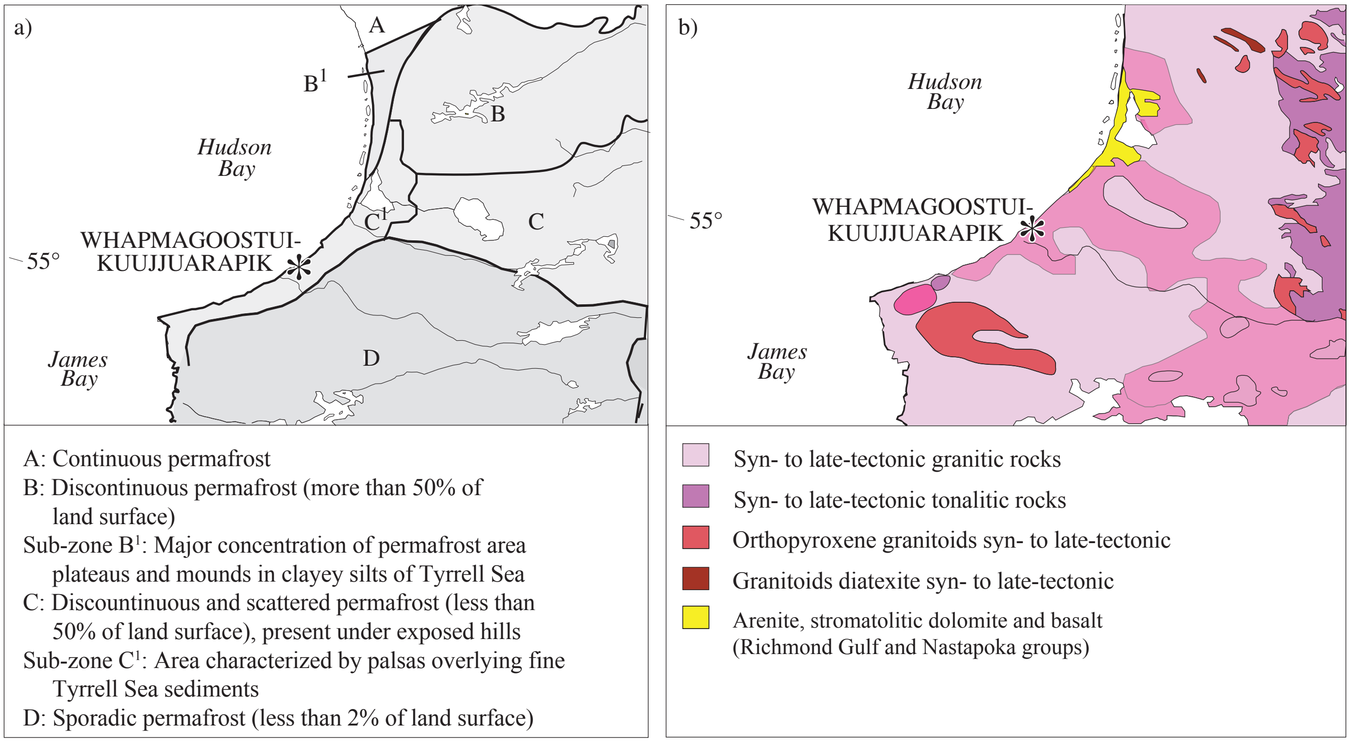

FIGURE 4. Permafrost distribution a) and geology b) of the Whapmagoostui-Kuujjuarapik area. Modified from (a) Allard and Seguin (1987) and (b) ministère des Ressources naturelles et de la Faune (2002).

On the cuestas ridges with a cliff on one side and gentle slope on the other of the Manitounuk Islands, data regarding permafrost distribution and thickness were collected via electrical resistivity surveys (Seguin & Allard, 1984; Figure 1, site 1; Figure 2f). In some places, permafrost can reach thicknesses of some 30 m, notably in the Proterozoic basalts and quartzites of the cuestas. The fact that there is no permafrost at altitudes of less than 20 m has been attributed to the moderating effect of the adjacent sea. Permafrost was also found in marine clays on the eastern side of Manitounuk Strait. Many periglacial landforms closely associated with the local presence of permafrost have been observed: thufurs (turf hummocks), heaved bedrock features, clastic dykes, and mud volcanoes. The cliff fronts of the cuestas are sites of rockfalls, which lead to the formation of taluses and boulder fields at the base of the cuestas (Belzile, 1984).

A synopsis of the early research on northern Quebec's permafrost, including the W-K region, is given in Allard and Seguin (1987). Based on Payette, Samson, and Lagarec (1976) and regional observations, this study demonstrated the close relationship among the presence or absence of permafrost, its thickness and thermal regime, the snow cover, and the structure of the forest cover. On the basis of these many relations, the authors proposed a permafrost distribution map (Figure 4a; Payette, 2001). A digital landform model was also devised for various sectors of a cryogenic plateau in the Manitounuk Islands. Winds, vegetation, and topography were used to forecast snow cover potentials. The results suggest that the state of the permafrost may vary over even short distances as a function of local conditions, particularly topography, vegetation, and snow cover (Roche & Allard, 1996). This analysis was for the period immediately prior to the marked recent warming of the W-K region, and thereby establishes a useful set of baseline conditions.

The study of cryofacies making up a permafrost plateau along the inner coastline of Manitounuk Strait showed that different thermal regimes generating different geomorphological evolutionary processes can indeed coexist within a single plateau (Caron, 1995). The evolution of this permafrost plateau was reconstructed through the use of thermistor cables, cryostratigraphy, repeated snow sampling, and a dendrochronological analysis of the spruce trees that colonized the plateau's summit and flanks (Allard, Caron & Bégin, 1996; Figure 1, site 2). Four distinct cryostratigraphic layers were identified (I, II, III, and IV), which can be differentiated by the structure and quantity of their ice content. The data showed that around 1830, Layer III, which is low in ice content, was formed during the first few years of frost penetration. The permafrost subsequently deepened, inducing the formation of ice-rich Layer IV. Since 1940, thermokarstic marshes have been the dominant form around the edges of the plateau, while forest cover became established in the depressions and on the slopes. Also since the late 1940s, degradation of permafrost plateaus along the coast is responsible for coastal retreat despite the general land uplifting that is taking place due to rapid postglacial rebound (Beaulieu & Allard, 2003).

Geology, geomorphology, and the Quaternary

GEOLOGY AND GEOMORPHOLOGY

There are 2 distinct physiographic assemblages in the W-K region (Figure 4b): 1) the Archean granito-gneissic basement forming the majority of the continent, whose relief essentially consists of low rolling hills and depressions that are generally aligned along an east–west structural axis; and 2) volcano-sedimentary formations constituting a string of islands (the Manitounuk Islands) that rise in the form of cuestas paralleling the coast, the offshore side of which slopes down to the sea at an angle of 5 to 10 degrees. Biron (1972) conducted a study of the area's geology that greatly built on and extended previous observations (Biron, 1972 and references therein; Kranck, 1951; Woodcock, 1960; Eade, 1966; Stevenson, 1968; Dimroth *et al.*, 1970). The Proterozoic rocks along the edge and just offshore of the Hudson Bay coast were named the Manitounuk Supergroup. This supergroup has been divided into 3 separate assemblages distinguished on the basis of angular discordance: the Pachi Group, the Richmond Group, and the Nastapoka Group. According to Chandler and Parrish (1989), the formation of Richmond Gulf Group is related to the initial rifting of the Trans-Hudson Orogen. The Proterozoic rocks found in the W-K area belong to the Nastapoka Group, composed of stromatolithic dolomites overlain by quartzites and basalts. A peperite deposit studied by Biron (1972) demonstrated that the site is the result of a blend of fluidal lavas and dolomitic muds.

Formations whose age range lies between the Proterozoic and the Quaternary do not exist in the region. Quaternary sedimentary coverage is discontinuous; fluvioglacial and morainic deposits exist as outcrops overlying the Precambrian basement. Marine clay deposits have filled the bottoms of larger valleys and structural depressions. Sandy deposits of marine, deltaic, or fluvial origin were sifted by wind action, leading to dune formation in some places (see below).

Deglaciation and the rate of isostatic uplift east of the region were first studied by Lee (1960; 1962). The first geomorphological data for the W-K region were gathered over the course of the "Hudsonie" project (Hamelin & Cailleux, 1968). The descriptions of landforms at that time paved the way for proper identification of the region's major geomorphological characteristics and processes (Cailleux, Hamelin & Cartier, 1968; Hamelin & Cailleux, 1968; Cailleux & Hamelin, 1969; Hamelin & Cailleux, 1969; Portmann, 1970; 1971; Hillaire-Marcel & de Boutray, 1975). The region has conspicuous glacial and postglacial features. Geomorphological features such as crests, lakes, and valleys are all aligned along 2 major axes (60° N and 110° N). Glacial striations occur in 2 main directions, NW and WSW (Parent, Paradis & Boisvert, 1995). There are abundant vestiges of the Tyrrell Sea, including boulder fields, shelly clay, terraces, a delta, and coastal dunes. Peatland palsas were also inventoried and described. Based on the stratigraphy of unconsolidated deposits in the region, Hillaire-Marcel and de Boutray (1975) were able to reconstruct the main deglaciation stages: deposition of the Sakami moraine, a lacustrine or marine phase distinguished by ice-contact fans, then a series of rhythmites followed by transgressive deposits from the Tyrrell Sea under a layer of regressive, deltaic, and alluvial sediments. The rapid isostatic uplift of the region was described by Andrews (1968) and Hillaire-Marcel (1976). It was concluded that the late-Wisconsinian flow of ice was toward the west, indicating that it radiated outward from the middle of the Quebec-Labrador peninsula. As in other regions along the Hudson Bay coastline, isostatic uplift continues to be among the most rapid in the world, at *ca* 13 mm·y^{-1} (Lavoie, 2006).

The study of multiple forms of erosion and uplifted littoral accumulations has enabled measurement of the emergence of the eastern Hudson Bay coastline, which began about 8000 cal. y BP (Allard & Tremblay, 1983a; Lavoie, 2006). The rate of emergence was quite high at the outset (on the order of 9–10 m per century; Lavoie, 2006) but diminished significantly thereafter to settle at approximately 1 m per century as of about 2800 cal. y BP. Similar results have been obtained for other parts of the region (Figure 5) (Ricard & Bégin, 1999; Cayer, 2002; Miousse, Bhiry & Lavoie, 2003; Drouin, 2004). The emergence curve for the past thousand years provides a maximum date for the inception of many terrestrial landforms and processes at elevations below 250 m in the coastal region, including periglacial processes, formation of permafrost, peat inception, formation of soils, aeolian processes, isolation of lacustrine basins, and initial colonization by vegetation.

The Quaternary deposits in Manitounuk Strait have been identified through seismic stratigraphy (Hill, Simard & Héquette, 1999; Figure 1, site 3). Three distinct acoustic units were identified. The bottom layer, Unit 1, is stratified and seems to be of glacio-marine origin. The median layer, Unit 2, is made up of current- and gravity-driven deposits that were established during a period of numerous earthquake events. Unit 3 is of marine origin, which was confirmed by its content of pollen grains and dinoflagellate cysts. On the eastern shore of Manitounuk Strait, 3 types

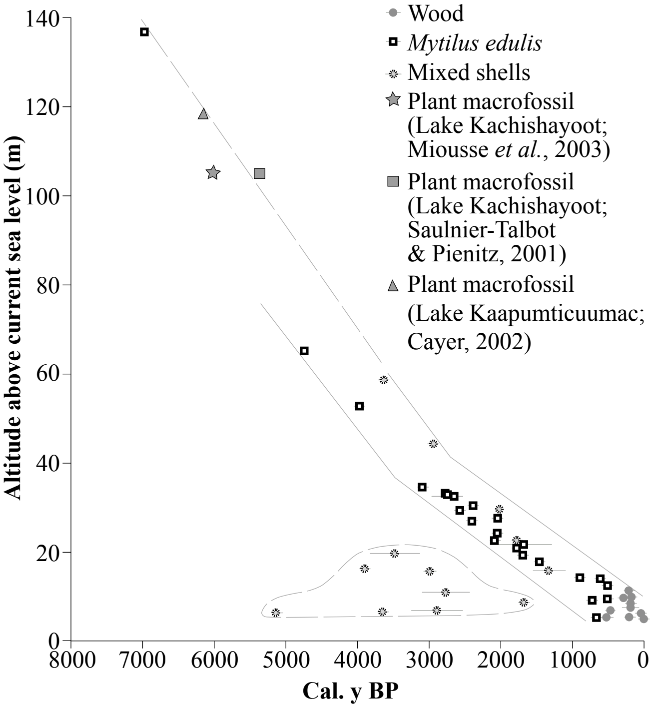

FIGURE 5. Emergence curve of the Whapmagoostui-Kuujjuarapik area. Modified from Allard and Tremblay (1983), Saulnier-Talbot and Pienitz (2001), Cayer (2002), and Miousse, Bhiry, and Lavoie (2003).

of staged shoreline have been identified (Ouellon, 1997). Between 120 and 90 m altitude, irregularly shaped paleoshoreline rocks or boulders have been laid at the foot of slopes. Between 90 and 20 m, the raised shorelines are characterized by sandy sediments that have occasionally been sorted by wind action. At 20 to 0 m altitude, shoreline sediments are fine-grained and more susceptible to permafrost formation and freeze–thaw processes.

COASTAL DYNAMICS

Allard and Tremblay (1983a,b) described the action of frost riving in bedrock along the shoreline. The *roches moutonnées* and the glacially polished surface on the basalt of the Manitounuk Islands are becoming locally dismantled and eroded by the combined action of gelifraction, sea push ridges, and storm waves. Through radiocarbon dating of raised cobble beaches and cobble fields they also concluded that cold periods such as the Little Ice Age favoured ice push features along the coast rather than wave-borne cobble beaches. In the W-K region, shoreline dynamics are governed by the combined influences of gelifraction (and/or the ice foot), storm surges, tidal currents, and sea-ice–related processes. Bégin (1981) studied shore ice processes and their impacts along the shores of the estuary of the Great Whale River and on the raised shores of the Tyrrell Sea. During the 4 successive stages of the ice season (freeze-up stage, ice formation on shorelines and water bodies, full winter stage, and finally estuarine and marine break-up stage), frost and ice play a major role in the formation of sandy/rocky beaches and foreshores (Bégin, 1981; Bégin & Allard, 1982).

A study of the littoral dynamics of a small bay with coastal mudflats on the eastern shore of Manitounuk Strait identified numerous features built up by frost action (Moffet, 1987): laminar clay flows, clastic dykes, frost-heaved boulders, and stone circles. A neighbouring low terrace featured frost cracks, frost boils (ostioles), frost mounds, and frost blisters. This study suggested that storm surges pushed the shoreline far inland between 1952 and 1974. However, periglacial processes, as controlled by the ice foot and its own thermal regime, seem to have been the main factors in the littoral dynamics of the soft deposit shoreline in Manitounuk Strait (Allard *et al.*, 1998; Ruz & Beaulieu, 1998; Beaulieu & Allard, 2003). The gradual penetration of frost under the ice foot that covers the clayey shoreline has led to the formation of segregation ice, the damming of groundwater flow (translating into icings), frost blisters, and lens-shaped bodies of intrusive ground ice (hydrolaccoliths) (Allard *et al.*, 1998). During ice melting in spring, landforms cave in and collapse and mud flows are common. The released sediments are then washed away by wave action and tidal currents.

Héquette, Tremblay, and Hill (1999) found that free-drifting floebergs, which initially form as pressure ridges in Hudson Bay, also play a major role in the erosion of nearshore unconsolidated sediments in the Manitounuk Strait (Figure 1, site 4). High-resolution seismic profiles indicate that in areas where water depth is less than 15 m and where waves are of low energy and the currents are weak, a 10-m-thick layer of sediment has been progressively eroded away by ice keels as uplift raised the bottom over time. This implies that hydraulic processes alone cannot explain all the observed nearshore seabed erosion, which is largely caused by ice scouring, resuspension of unconsolidated sediments, and their subsequent advective loss from the site by currents. This mechanism also partly explains the erosional nature of the tidal flats in the strait, which essentially consist of Holocene marine sediments overlain by a veneer of modern intertidal deposits (Ruz *et al.*, 1998; Ruz, 2005).

Cloutier (1996) demonstrated that littoral forms such as beaches develop more slowly along the Hudson Bay coast than along temperate coasts due to the inertia of cold-water masses. Nevertheless, sudden changes in these coastal landforms can occur, caused by the high energy waves and currents associated with storms, principally in autumn. Measurements of longshore sand transport near the mouth of the Great Whale River estuary showed that considerable increases in bedload and suspended sediment transport occur during fall and freeze-up seasons compared to summer (Héquette & Tremblay, 2009). The increase in sediment transport associated with low water temperatures is believed to be mainly due to lower sediment fall velocities resulting from an increase in fluid viscosity. These results suggest that in cold climate regions there may be a substantial increase of coastal sediment transport during near-freezing water conditions.

WIND ACTIVITY AND DUNE-BUILDING

Dunes and other eolian landforms in the W-K region were intensively studied by Filion and Morisset (1983), Filion (1983; 1984a,b), Bélanger and Filion (1991), Filion *et al.* (1991), Marin and Filion (1992) and Saint-Laurent and Filion (1992). Virtually all of the region's dunes are of the parabolic type, although their spatial arrangement reflects the variable direction of the wind and local ecological conditions. In the boreal and sub-boreal zones of the forest tundra, for example, the dunes are perpendicular, opposite, and hemicyclic, as a result of the multidirectional winds from the N, SE, S, or SW (Filion & Morisset, 1983). In the shrub sub-zone of the forest tundra, dunes are imbricated or laid out in step-wise fashion, reflecting their deposition by easterly winds (Figure 6). The dunes may move and grow in forested sites, burying trees located on the leeside of the front and further exposing them in the inner depression with dune progression. White spruce so affected can adapt to sand deposition and erosion by developing growth forms enabling them to survive (Marin & Filion, 1992; Figure 1, site 5). As expected, forest cover influences the progress of the dunes. As an example, trees growing between dune ridges force the ridges to move and expand in diverging directions under the multidirectional effects of the wind, resulting in digitate dunes (Figure 6).

This close relationship between dune activity and plant cover was recorded in the course of stratigraphic analysis of dune deposits and paleosols, enabling Filion (1983; 1984a,b) and Filion *et al.* (1991) to document wind activity in relation to climate during the Holocene. Several periods of high wind activity were recorded after 5000 BP, with a periodicity of 350 to 400 y, especially between 3250 and 2750 y BP, 1650 and 1050 y BP, and

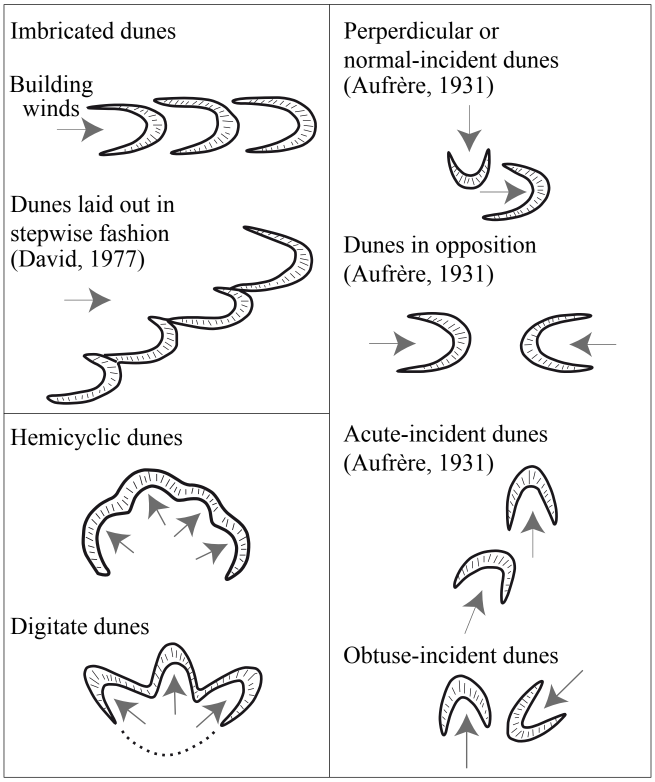

FIGURE 6. Spatial arrangement of the parabolic dunes in the Whapmagoostui-Kuujjuarapik area. Modified from Filion and Morisset (1983).

750 y BP to present. Buried organic horizons in sand dune deposits attest to the alternating phases of stabilization (by vegetation and soil formation) and wind erosion. Charcoal fragments in the organic horizons bear witness to the determining influence of forest fires at the site scale. Soils are exposed after a fire event, becoming vulnerable to winds, which can be very strong. It takes a long time for plants to colonize barren mineral surfaces, enabling the wind to rework the sediments, thus burying certain organic horizons previously spared from wind erosion. Analysis of frost features (such as frost cracks) in numerous paleosols and comparisons of wind activity with the effects of gelifluction in the region indicated that this dune–fire relationship established during periods of climatic cooling. The sediments forming the dunes in this region consist of wind- and snow-borne deposits, termed niveo-eolian. The second type is defined as sandy deposits mixed with annual snow. They can also form alternating layers of sand and snow of variable thickness in the centimetre range (Rochette & Cailleux, 1971; Cailleux, 1972; 1976).

Bélanger and Filion (1991) undertook year-round measurements (1987-1988) to test the hypothesis that wind-and-snow processes are more effective than wind processes alone in building subarctic dunes. They found that niveo-eolian sand deposition during the snow season contributed > 75% of the total annual accumulation in exposed sites and < 25% in forest sites. The maximum thickness of interstratified snow and sand deposits (3.5 m) was reached in March. Bélanger and Filion (1991) also found that niveo-eolian sand deposition and spring thaw were responsible for major damage to trees growing close to active dune ridges.

The pivotal role of niveo-eolian sand deposition was also noted with respect to the formation of a series of dunes paralleling the beach at W-K. These dunes likely developed during periods of low sediment transport and slow beach aggradation (Ruz & Allard, 1994, Figure 1, site 6). They probably formed in conjunction with isostatic uplift, at the rate of 1 dune series every 100 y (Ruz & Allard, 1994). Niveo-eolian sand sedimentation during the snow season was found responsible for coarse-grained sand beds in vegetated coastal dunes (Ruz, 2005). In non-vegetated dunes, coarse-grained sand beds were reshaped after the melting of snow interstratified with sand. The coastal aggradation plain is thus made up of a series of parallel dunified beach ridges in which niveo-aeolian processes play a role (Ruz & Allard, 1995).

At many sites located close to or within W-K, wind-borne sediments have been reworked by human activities. A military base was erected at this location in 1955 and 2 landing strips were built across the village, which initiated the destruction of the plant cover and subsequently exposed the sand surface to wind erosion. This situation is worsening as the village expands and as all-terrain vehicle use increases (Desormeaux, 2005). There are ongoing studies by CEN researchers to develop plant restoration strategies for remediating these effects.

LANDSLIDES

Past landslides in the W-K region had an impact on the sandy terraces located on the left bank of the Great Whale River. Over about a dozen kilometres, from its mouth to the first waterfalls, landslide scars were first reported by Cailleux (1972), Portmann (1972), and Demangeot (1974). The morphology, chronology, and interpretation of these landslides were studied by Bégin and Filion (1987; 1988). Using topographical and stratigraphical data, they found that the scars were associated with rotational and retrogressive landslides (Figure 1, site 7). Each formed at a different time, with major landslides between 3200 and 2200 y BP, about 2200 y BP, and 900 y BP. The recent mass movements were tree-ring dated. Two slides occurred simultaneously in 1818, and 2 others around 1839 and 1846. Recent mass movements were attributed to cool, damp climatic conditions that may have increased the soil moisture content and raised interstitial pressures.

Paleolimnology of shallow lakes and ponds

Lakes and ponds are a common feature of the landscape around W-K, and limnological, paleolimnological, sedimentological, and paleoecological studies have been conducted at several sites. One of these study sites, Lake Kachishayoot (Figure 1, site 8; Figure 2d), is located 10 km north of W-K, and its isolation from the sea during the Holocene by uplift and subsequent development as a freshwater coastal basin were documented in 2 complementary studies. First, an analysis by Saulnier-Talbot and Pienitz (2001) of the sedimentary diatom assemblages from a core recovered from Lake Kachishayoot enabled the identification of 3 successive stages of the lake basin (Figure 7). These stages are linked to the local, rapid rate of isostatic rebound: a marine stage that ended towards 4500 cal. y BP, a stage of gradual isolation of the lake basin from the postglacial marine waters that lasted from about 4500 to 1600 cal. y BP, and finally the modern lacustrine stage from 1600 cal. y BP to present. Interpretation of this sequence of events was supplemented by the quantitative reconstruction of lake water alkalinity using a diatom-based inference model developed for Labrador lakes by Fallu, Allaire, and Pienitz (2002). The inferred values showed a significant gradual decrease of alkalinity over the course of the Holocene, with values falling from 267 to 29 μeq·L^{-1} as solute concentrations plummeted when the lake was ultimately cut off from the sea.

The second study at Lake Kachishayoot (Miousse, Bhiry & Lavoie, 2003) combined sedimentological, macrofossil, and pollen data and identified 2 periods of major lake-level fluctuations after its isolation some time during the Late Holocene: a rise in water level occurring after 3620 cal. y BP and a decrease that started a little before 2250 cal. y BP. This fluctuation was also recorded in Lake Kaapumtikumac, located about 1 km from Lake Kachishayoot (Cayer, 2002) and in a system of 3 interrelated lakes a few kilometres northeast of Lake Kachishayoot (Laframboise, 2011).

Limnological and paleolimnological research in the W-K region has also advanced our understanding of underwater lake optics and enabled the development of a novel paleolimnological tool: paleo-optics. The limnological research was initiated by Laurion, Vincent, and Lean (1997), who developed underwater spectral irradiance models in relation to dissolved organic carbon (DOC) and chromophoric dissolved organic matter (CDOM) concentrations in the lake waters. Vincent, Laurion and Pienitz, (1998) subsequently developed an optical model that enabled the reconstruction of past light fields in lakes based on CDOM and DOC estimations. Gibson, Vincent, and Pienitz (2001) described short-term (hours, days) and long-term (weeks) CDOM dynamics, the importance of diurnal stratification and UV-photodegradation processes, and the variability that aquatic organisms are subjected to as they are exposed to UV radiation in their natural environment. UV attenuation in the surface waters of Lake Kachishayoot decreased in the morning by up to 20%, indicating UV-photodegradation of CDOM, followed by an increase in the afternoon with wind-induced mixing and entrainment of non-UV-exposed deeper waters. Overall, CDOM absorbance of the lake water decreased by around 20% during the June–July period and then rose again with increased precipitation and terrestrial runoff in August. To extend this work, Fallu and Pienitz (1999) developed a diatom-based transfer function to quantitatively infer past levels of DOC in northwestern Quebec lakes. All these models were subsequently applied to a sedimentary diatom sequence from Lake Kachishayoot (Saulnier-Talbot, Pienitz & Vincent, 2003). The historic variations in diatom-inferred DOC

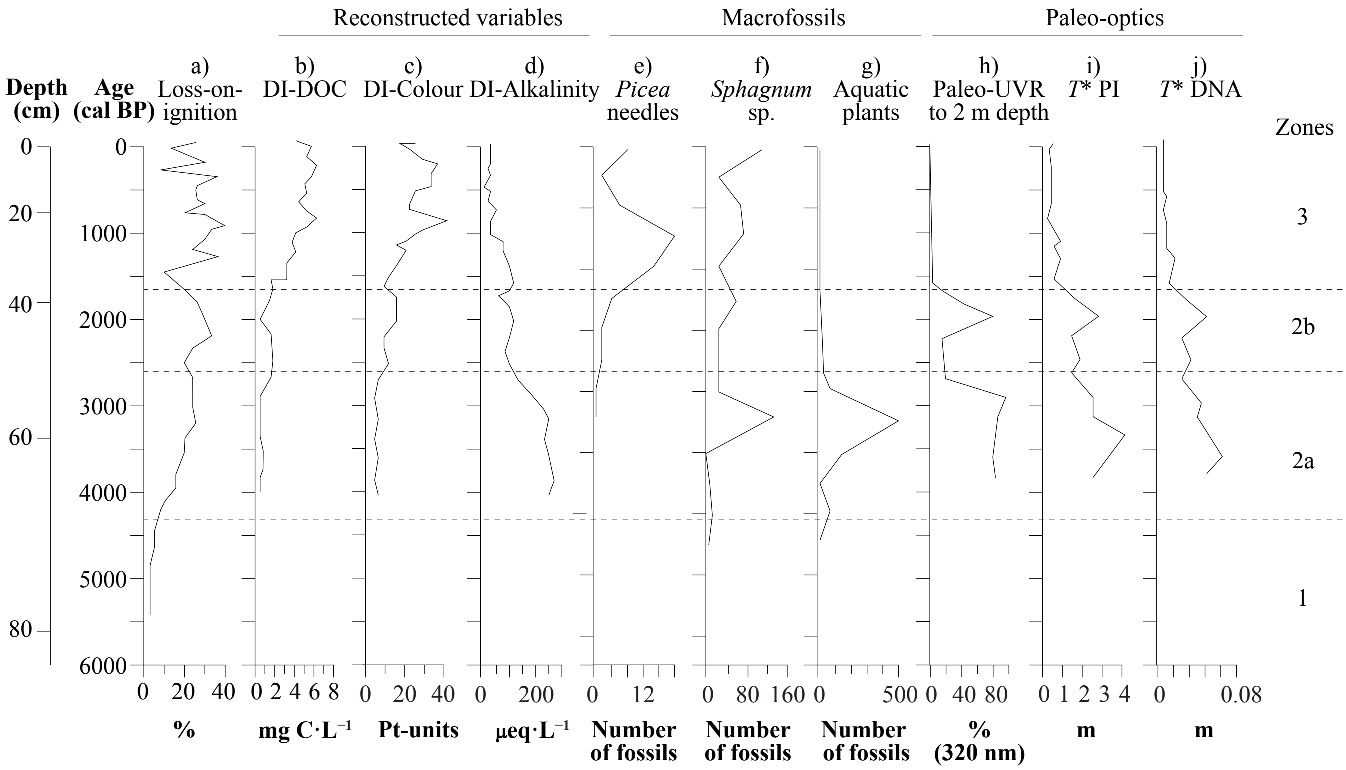

FIGURE 7. Limnological and paleo-optical changes in Lake Kachishayoot. Modified from Saulnier-Talbot, Pienitz, and Vincent (2003). DI-DOC indicates diatom-inferred dissolved organic carbon; DI-Colour indicates diatom-inferred water colour; DI-Alkalinity indicates diatom-inferred alkalinity; *T** PI is an underwater UV exposure index for photoinhibition of photosynthesis; *T** DNA is an underwater UV exposure index for DNA damage. The 4 zones correspond to the changes in sedimentary diatom assemblages identified by cluster analysis.

levels (DI-DOC) reflected plant succession and soil changes in the lake catchment; DI-DOC and *Picea* sp. macrofossils were significantly correlated: $r = 0.62$, $n = 15$, $P < 0.05$. DI-DOC values were then incorporated into optical models developed by Vincent, Laurion, and Pienitz (1998) and Gibson *et al.* (2000), enabling the reconstruction of past light fields in the lake over a 4000-y period and the application of 2 biological UV exposure indices. These show how the aquatic biota were highly exposed to UV in the initial stages of the evolution of the lake, with a pronounced fall in exposure associated with increased inputs of UV-absorbing DOC from the developing vegetation and soils in the catchment (Figure 7).

Lake Kachishayoot continues to be monitored (using data-loggers) and was recently included in a Canada-wide study of recent and historical mercury deposition (Muir *et al.*, 2009). This latter study showed that, consistent with data from other high-latitude lakes, the input of this toxic metal from long-range anthropogenic sources is continuing to increase.

The sedimentology and isotopic chemistry of sediments in Lake Kaapumtikumac (about 1 km from Lake Kachishayoot; Figure 1, site 11) tracked the almost continuous evolution of the region's climate from the Hypsithermal, a Holocene period characterized by warm conditions during which there was terrestrialization of shallow areas of the lake, to the Neoglacial, which was marked by cooler, more humid conditions separated by 2 brief warmer episodes. The first warm episode occurred between *ca* 2000 and 1150 cal. y BP and the second between *ca* 750 and 500 cal. y BP (Cayer, 2002).

Diatom assemblages were analyzed in 12 lakes of the region, and the data collected were included in the aforementioned transfer function developed to infer DOC in northwestern Quebec. This study (Fallu, Allaire & Pienitz, 2000) also produced an illustrated flora of the sedimentary diatoms of northwestern Quebec from the boreal forest zone to the tundra zone, which remains to this day an important reference for arctic and subarctic diatom studies. The same lakes were later used to investigate relationships between chironomid assemblages and various environmental variables and ultimately to develop a chironomid-based transfer function to infer mean August air temperatures (Larocque, Pienitz & Rolland, 2006). Finally, a study by Swadling *et al.* (2001) investigated copepod biogeography and the relationships between their distribution and various environmental variables in 37 lakes and ponds near W-K. Up to 4 species were recorded per lake. The dominant species were *Leptodiaptomus minutus* and *Acanthocyclops vernalis*, and in general the assemblages resembled those in forested regions of southern Quebec. Two notable exceptions were *Leptodiaptomus tyrrelli*, previously only recorded west of Hudson Bay, and *Hesperodiaptomus arcticus*, previously only recorded north of 58° N.

Paleolimnological, sedimentological, and limnological studies have been conducted on thermokarst lakes and ponds in a small valley of the Kwakwatanikapistikw River, a right-bank tributary of the Great Whale River (55° 19.853' N, 77° 30.166' W). The ponds result from the thawing of permafrost mounds, mainly mineral palsas (lithalsas; see below), and are varied in colour as a result of differences in dissolved organic matter and suspended sediment (Watanabe *et al.*, 2011). Despite their shallow depths (1.5–3 m) they are highly stratified, with anoxic bottom waters, and they are biogeochemically active sites of greenhouse gas production (Laurion *et al.*, 2010). This site has undergone major landscape and limnological changes due to the accelerated thawing of permafrost over the last centuries (Bouchard *et al.*, 2011).

Soils

The main superficial deposits and extant soils in the W-K region were mapped by Payette (1973). Lithosols and lithic regosols predominate, while podzols are limited to a few well-drained forested sites. Brunisols are relatively common, as they develop in well-drained sites. These soils form a pedogenetic chronosequence associated with isostatic uplift. This chronosequence includes a series of poorly developed (lithic and orthic regosols), moderately developed (brunisols), and well developed (podzols) soils. Gleysols and fibrisols (palsas) occur at poorly drained sites. The soils of the region are affected by wind activity, which is variable over time and leads to either soil stabilization or erosion. Many soil types are actually buried by wind-borne sediments (Filion, 1983). Most dune paleosols belong to the larger group of dystric brunisols, while active dune fields give rise to orthic regosols. As in other subarctic zones, podzolized soils characteristically feature patches of light-coloured sand (whitish-grey) in contrast to the reddish colour of horizon B (Bf or Bfh) (Payette & Filion, 1993a). The initiation of these patches was attributed to the large quantity of snow accumulating in forest or krummholz environments and the resultant meltwater percolating into the still-frozen ground after the thaw (Payette & Filion, 1993a).

Current vegetation

The W-K region is located in the forest sub-zone of the forest tundra (Payette, 1976; 1983). Conifer forests are confined to unconsolidated deposits and sites sheltered from extreme weather conditions. Vegetation types (Payette & Gauthier, 1972; Figure 8) include grass-dominated cover along the coast, lichen-heath cover on rocky outcrops, and lichen-spruce woodlands on the sandy terraces located along the south shore of the Great Whale River. The distribution of these communities was attributed to the successional gradient, the thickness of unconsolidated deposits, and soil drainage patterns (Payette & Gauthier, 1972). The dominant tree species are white spruce (*Picea glauca* [Moench] Voss.), black spruce (*Picea mariana* [Mill.] B.S.P.), and eastern larch (*Larix laricina* [Du Roi] K. Koch). A balsam poplar clone (*Populus balsamifera* L.) was recorded some 5 km from the village, on the north shore of the Great Whale River (Brodie, Houle & Fortin, 1995; Figure 1, site 9), and covered a surface area of about 2000 m^2. This poplar stand was a monoclonal population approximately 60 y old.

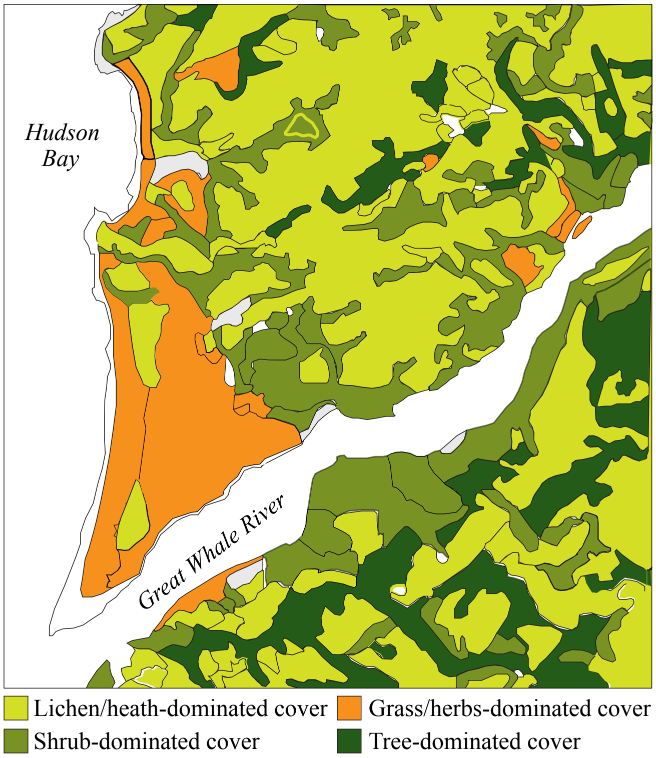

FIGURE 8. Vegetation cover in the Whapmagoostui-Kuujjuarapik area. Modified from Payette and Gauthier (1972).

The coastal portion of the forest tundra is dominated by white spruce forests (Hustich, 1950; Payette, 1983), although this species is limited to a strip about 10 km wide along the coast of Hudson Bay. This distribution is attributable to the seasonal maritime climate and to relatively infrequent forest fires (Payette & Filion, 1975; Payette, 1993; Ricard & Bégin, 1999). In the W-K region, there are mixed populations of white spruce and black spruce about 8 km from the shore of Hudson Bay. In inland continental sites, pure black spruce stands are found. Eastern larch predominates at moist, minerotrophic sites, notably at lake margins and in peatlands.

The flora of the W-K region is of the subarctic type, in which the percentage of Arctic taxa divided by the percentage of boreal taxa is < 1 (Morisset, Payette & Deshaye, 1983). Approximately 400 taxa have been identified so far: ~29% are Arctic or Arctic-alpine taxa, 69% are boreal, and less than 2% are introduced species (Forest & Legault, 1977; Morisset, Payette & Deshaye, 1983). Lichen–spruce forests close to the village of W-K are found on the sand terraces along the south shore of the Great Whale River (Figure 2e). Shrubs include dwarf birch (*Betula glandulosa* Michx.) and several ericaceous species (*Rhododendron groenlandicum* Retzius, *Vaccinium uliginosum* L., and *Vaccinium vitis-idaea* L.). Most trees are less than 200 y old. Recurrent forest fire and logging by indigenous populations have largely limited the development of old-growth forests (Delwaide & Filion, 1987). In landslide landforms, vegetation is a function of drainage conditions. In well-drained landslide scars (initiation zones), lichen–spruce woodlands developed, whereas wet accumulation zones contain moss–spruce forests (Bégin, 1985). High shrubs, mainly *Salix planifolia* Pursh and *Alnus viridis* var. *crispa* (Aiton) House, colonize the outside fringe of slide zones.

On the terraces south of the Great Whale River, lichen–spruce woodlands have been fragmented by postfire wind activity, and small dunes can be found within the forests (Filion & Morisset, 1983; Filion, 1984a). Tree-ring analysis of partly buried trees exposed as the dune fronts progress has yielded information on rates of accumulation, erosion, and migration of cold-climate dunes (Marin & Filion, 1992). Reduced radial growth and anatomical modifications (increase in tracheid size) are notable features of the buried white spruce stems (Cournoyer & Filion, 1994).

The area located northeast of the village of W-K is characterized by a zone of granitic outcrops and boulder fields, where the thin organic deposits can only support low plant communities (Payette & Gauthier, 1972). In exposed sites, the lichen–heath cover includes various species of *Rhododendron* and *Vaccinium* and a slow-growing ground bearberry willow, *Salix uva-ursi* Pursh (Bélisle & Maillette, 1988; Maillette, Bélisle & Seguin, 1988; Figure 1, site 10). A study conducted on 364 individual willows concluded that the growth rate, vegetative reproduction, and extended longevity of this species all contributed to its survival in highly exposed environments. Although most willows studied were less than 100 y old, one 170-y-old individual was inventoried (Bélisle & Maillette, 1988).

Conifer forests are confined to the valleys and depressions where unconsolidated deposits enabled thicker soils to develop. In one of the structural valleys northeast of W-K, the Cri Valley, old-growth forests were found (Figure 2b). They were established on coarse material (boulders and coarse-grained sand), where degraded dystic brunisols developed (Payette, 1973). The oldest white spruce trees sampled were about 350 y old (Filion & Payette, 1982; Caccianiga, Payette & Filion, 2008; Figure 1, site 11). The valley has likely been saved from logging due to its distance from W-K. The absence of deadwood on the floor suggests that these white spruce forests were the first to colonize this site and probably established at the same time as many other white spruce forests at the northern limit of the species along the Hudson Bay coast (Caccianiga & Payette, 2006). The age, height, and diameter structures of these stands seem to reflect an episodic regeneration associated with climatic conditions (Payette, 1976). Shrubs include *Betula glandulosa* Michx., *Rhododendron groenlandicum* Retzius, *Salix glauca* L., *Alnus viridis* var. *crispa*, and *Viburnum edule* Raf. Mosses consist mainly of *Pleurozium schreberi* Brid. Mitt. and *Dicranum fuscescens* Turn.

In exposed sites, tree species develop various growth forms, the most common being prostrate forms in response to the severe winter conditions (Payette, 1974). In exposed sites in the upper Cri Valley, Filion and Payette (1982) reported the presence of whorls at the snow–air interface on trees forming a small grove. Increased radial growth indicated that growth conditions improved after 1870, enabling the stems to develop normally above the snow–air interface. Caccianiga, Payette, and Filion (2008) also reported such changes in tree growth dating from the middle of the 19th century.

The climatic and soil conditions of the W-K region are also favourable to the formation of snow beds, which are close to their southern range limit in this area (Filion & Payette, 1976). Large amounts of snow accumulation and late snow thaw considerably reduce the length of the growing season and favour a particular form of vegetation, said referred to as chionophilous (Filion & Payette, 1982). More than 75% of the species recorded in the Cri Valley snow beds were Arctic-alpine species (Filion, 1976).

Holocene vegetation

The W-K region was afforested shortly after glacial retreat and coastal emergence. The oldest paleoecological data from the area are from a small lake located 10 km northeast of the village (Laframboise, 2011). Spruce needles were found near the base of a core dated at 6425 cal. y BP. According to pollen assemblages from this site, the initial vegetation likely corresponded to an open forest dominated by spruce, green alder, and dwarf birch (Laframboise, 2011). Macrofossil data from a palsa peatland 8 km southeast of Kuujjuarapik (Figure 1, site 12; Figure 2c) also suggest early colonization of trees on the recently emerged lands; macroremains of eastern larch, located at the base of the peat deposit and dated to 5790 cal. y BP, and black spruce needles and seeds dated at 5300 cal. y BP were found (Arlen-Pouliot & Bhiry, 2005).

Pollen analysis of sediments from 2 lakes about a hundred km upstream of the Great Whale River provided additional information on the regional postglacial vegetation history (Gajewski, Payette & Ritchie, 1993; Gajewski, Garralla & Milot-Roy, 1996). The bottom of the oldest sequence (Lake GB2; Gajewski, Payette & Ritchie, 1993) was characterized by relatively low pollen concentrations indicating an open environment dominated by shrubs and grasses (*Salix* sp., Ericaceae, *Lycopodium* sp., and *Sphagnum* sp.). A densification of the forest cover occurred between 6330 and 5720 cal. y BP, as indicated by an expansion of shrub and tree species (*Alnus* sp. [likely *A. viridis* var. *crispa*], *Betula* sp., and *Picea*), followed by a steady decrease in pollen representation of these species until the present. The opening of the forest cover that has been taking place since 3000 y BP could be attributed to a climatic cooling (Neoglacial period) and weak post-fire tree regeneration (Gagnon & Payette, 1985).

A macrofossil and pollen study of organic horizons buried in the wind-borne sands in the terraces south of the Great Whale River also indicated rapid local afforestation (Filion, 1984b). The establishment of the terrace towards 2740 cal. y BP (Hillaire-Marcel, 1976) was soon followed by the arrival of Poaceae grasses, mostly of the genera *Glyceria* and *Festuca*. Macroremains of spruce, *Juniperus communis* L. and *Empetrum nigrum* L., were also found during this phase. After 1360 cal. y BP, the floristic composition corresponded to a typical forest community. Another study of dune paleosol macrofossils, located a few hundred kilometres upriver, also showed that spruce was present shortly after deglaciation (Desponts & Payette, 1993). For this inland site, the arrival of jack pine (*Pinus banksiana* Lamb.) after 3480 cal. y BP gave rise to a mixed community with black spruce.

Natural and anthropogenic disturbances

FIRE

The W-K region has experienced numerous fires since the vegetation first became established. Charcoal remains found in peat yielded the oldest ^{14}C dates, between 4100 and 4600 cal. y BP (Bhiry & Robert, 2006). The vegetation cover has burned over regularly since that time and macroscopic charcoal fragments are found throughout the peat sequence. A stratigraphic section excavated into eolian deposits on the upper terrace south of the Great Whale River enabled ^{14}C dating of 7 charred organic horizons (Filion, 1983). The oldest charred layer was dated 2430 cal. y BP, a date that is close to that (2220 cal. y BP) obtained by Miousse, Bhiry, and Lavoie (2003) for a site located 8 km northeast of the village. Other charcoal horizons were dated 1780, 1360, 1355, 600, and 530 cal. y BP (Filion, 1983; Figure 1, site 13), an indication that fires were recurrent during the late Holocene.

Fire scars found on spruce trees provide evidence for recent fires in the W-K region. Vachon (1980) identified several fires (1806, 1820, 1833, and 1897), which were dated by tree-ring methods, in a black spruce stand some 10 km upstream of the mouth of the Great Whale River (Figure 1, site 14). Many of the fires, which were likely small, may be attributed to the indigenous people who have occupied the area continuously over the past hundred years or so. In the Cri Valley, however, no fire marks (charcoal or fire scars) were found (Caccianiga, Payette & Filion, 2008).

Post-fire plant colonization was studied along a transect through a currently stabilizing wind-deflated surface on the sandy terraces south of the Great Whale River (Filion & Payette, 1989; Figure 1, site 15). Seven vegetation types corresponding to post-fire regeneration stages were described. The pioneer species *Polytrichum piliferum* Hedw., *Stereocaulon paschale* (L.) Hoffm., and *Rhacomitrium canescens* (Hedw.) Brid appear to have colonized the sandy substrate while it was still unstable. The intermediate stage was characterized by a lichen carpet dominated by *Cladonia mitis* Sandst. At this stage, desiccation cracks opened up the lichen carpet, enabling pioneer species to become established on the exposed sand beneath. Species diversity was greatest at this point but then steadily decreased until a lichen–spruce forest developed with the lichen *Cladonia stellaris* (Opiz) Pous & Vezda and ericaceous plants.

INSECT OUTBREAKS

Insect outbreaks in subarctic areas tend to be less devastating than in the boreal forest, but they can still cause major disturbances. Throughout the Quebec-Labrador peninsula, 21 outbreaks of the larch sawfly (*Pristiphora erichsonii* Hartig) affecting eastern larch populations have been identified over the last 3 centuries from radial-growth patterns (Filion, Cloutier & Cournoyer, 2010). In the W-K region, 6 outbreaks, starting in 1840, 1897, 1904, 1938, 1962, and 1968, were identified (Arquillière *et al.*, 1990; Filion, Cloutier & Cournoyer, 2010). Overall in the Quebec-Labrador region, it has been the sites along Hudson Bay, including W-K and Lac Guillaume-Delisle (Richmond

Gulf), that have been the least affected by the larch sawfly (Tailleux & Cloutier, 1993; Filion, Cloutier & Cournoyer, 2010). The cooler climate along the coast may have had a limiting effect on the larval development of this insect. Egg-laying scars on twigs are direct evidence of the activity of larch sawfly (Cloutier & Filion, 1991). Because egg laying occurs only on the current year's growth of larch long shoots, it is possible to date recent sawfly activity accurately, with the egg-laying scars remaining visible on long shoots for some 20 y (Tailleux & Cloutier, 1993).

Although its impact is less devastating than further south, the spruce beetle (*Dendroctonus rufipennis* Kirby) is also present in the W-K region. Many signs of its activity are evident among white spruce trees in the Cri Lake valley (Caccianiga, Payette & Filion, 2008; Figure 1, site 11). High tree mortality in the 1970s, 1980s, and especially 1990s was attributed to this insect, as evidenced by galleries at the wood–bark interface, especially among senescent trees. Pockets of resin, which can be seen on wood cross sections, also bear witness to spruce beetle activity. Finally, invasion of the wood by phytopathogens (genus *Ceratocystis*, *Ophiostoma*, or *Leptographium*), which generally follow in the wake of spruce beetle activity (Paine, Raffa & Harrington, 1997; Harrington & Wingfield, 1998), has also been observed. These studies and others have shown that spruce beetle has been attacking the spruce population recurrently since at least the 18th century (Caccianiga, Payette & Filion, 2008).

LOGGING

The Cree First Nation has long occupied the W-K area (see below) and did business with the Hudson's Bay Company trading post as soon as it was set up in the 18th century. The post was located at the mouth of the Great Whale River, and the Cree camped on either side of the river during summer. More than 200 campsites (Figure 2e) and small logging areas have been mapped and dated on the south shore of the Great Whale River (Delwaide & Filion, 1987). Logging was usually associated with campsites, but wood was also collected by Hudson's Bay employees for heating and for construction of the trading post buildings. Although quite dispersed throughout the area and variable in intensity, logging activities nevertheless affected the forest structure. About 40% of the forest area close to the village has been logged at least once over the past 150 y (Delwaide & Filion, 1987). Logging activities were especially important between 1954 and 1973. During this period, a large quantity of wood was cut near the village and carried away to be used as firewood. Logging for firewood substantially decreased from 1973 onwards as many homes in the settlement switched to oil-based systems for heating. In the logged areas, surviving trees whose radial growth increased significantly were used to accurately date several logging operations (Delwaide & Filion, 1987; 1988). Trampling around campsites and in logging areas also had an impact on forest regeneration. In sites where logging was intensive, the resulting removal of the lichen carpet favoured the establishment of white spruce seedlings (Delwaide & Filion, 1988). An experimental study in the W-K area showed that removal of the lichen carpet also favoured seedling establishment (Houle & Filion, 2003; Figure 1, site 16). At the end of the 3-y experiments, twice as many seedlings were established in test plots where lichens were removed than in control plots.

Coastal ecosystem dynamics

Plants play a major role in the processes of beach stabilization (Imbert & Houle, 2000; 2001). Primary succession on the upper reaches of beaches at W-K appears to be controlled by abiotic factors, particularly during the early stages of succession (Houle, 1997). This process begins with the establishment of *Honckenya peploides* (L.) Ehrh., a clonal sandwort that is resistant to wind erosion (Bournerias & Forest, 1975; Houle, 1996; Figure 1, site 17), and whose morphology favours sand accumulation. The buried stems develop adventitious roots as support for vertical and lateral growth. Low mounds built up by *Honckenya* may even coalesce over time to form small crests, allowing other species to establish, such as *Leymus mollis* Trin and *Lathyrus japonicus* Willd., at the base of the small coastal dunes (Houle, 1997). Micro-environments formed by *Honckenya peploides* (L.) Ehrh. help retain seeds and promote germination, establishment, and survival of *Leymus mollis* (Trin.) Pilg. at this stage of the succession (Gagné & Houle, 2002).

Inland, various grass and herb species (*Festuca rubra* L., *Hierochloe alpine* [Sw. ex Willd.] Roem. & Schult., *Chamerion latifolium* [L.] Holub, *Trisetum spicatum* [L.] K. Richt., *Epilobium angustifolium* L., *Sibbaldiopsis tridenta* [Aiton] Rydb., *Achillea borealis* Bong.) colonize higher and older dunes (Bournerias & Forest, 1975; Laliberté & Payette, 2008). Bryophytes are also found at this stage, the most common being *Drepanocladus uncinatus* (Hedw.) Warnst., *Hylocomium splendens* (Hedw.) Schimp., and *Dicranum elongatum* Schleich. ex Schwägr.

The establishment of white spruce along a successional gradient was studied at several sites along the shore of Hudson Bay, 3 of which are in the W-K region (Laliberté & Payette, 2008). At one site close to the mouth of the Great Whale River (Figure 1, site 18) the lower limit of individual trees was found to be at a distance of 50.5 m from the sea and an altitude of 5.15 m, and the limit of the forest was 83.4 m from the sea at an altitude of 7.32 m (Laliberté, 2006; Figure 9). Recent seedling establishment outside the lower tree limit suggests that favourable climatic conditions of the last century have contributed to lowering the tree limit, bringing it closer to the sea (Laliberté, 2006). The catalyst for soil development is the development of vegetation cover along the successional gradient. The bare soil forming the beach gives way to a regosol beneath the herbs and to a brunisol beneath the trees and forest (Laliberté & Payette, 2008).

Primary succession in more humid and sheltered coastal environments was also studied on the shores of Manitounuk Strait (Bégin, Bérubé & Grégoire, 1993). *Carex glareosa* Wahlenb, *Potentilla anserina* L., and *Arenaria peploides* L. are the first plants to colonize wet sites; these plants are then followed by shrubs, namely willows (*Salix planifolia* Pursh., *S. Glauca* L., and *S. candida*

Flügg) and dwarf birch. White spruce seedlings first establish among shrubs (Bégin, Bérubé & Grégoire, 1993; Ricard & Bégin, 1999), which play a major role in seedling survival. High shrubs allow snow to accumulate, which protects young seedlings (Ricard & Bégin, 1999; Figure 1, site 19). The situation becomes critical for both growth and survival of seedlings when they reach the upper limit of the shrub cover. Exposure to low temperatures and bud abrasion by windblown snow crystals may have a limiting effect on apical tree growth and induces the formation of multiple shoots. Tree establishment appears to be much more rapid in wet sites than in dry sites at similar rates of isostatic uplift. The average time for humid emerged surfaces to be colonized by spruce seedlings is about 100 y (120–140 m above high tide level; Bégin, Bérubé & Grégoire, 1993; Figure 1, site 20), while spruce can be assumed to have colonized dry substrates that were between 195 and 410 y of age (Laliberté & Payette, 2008).

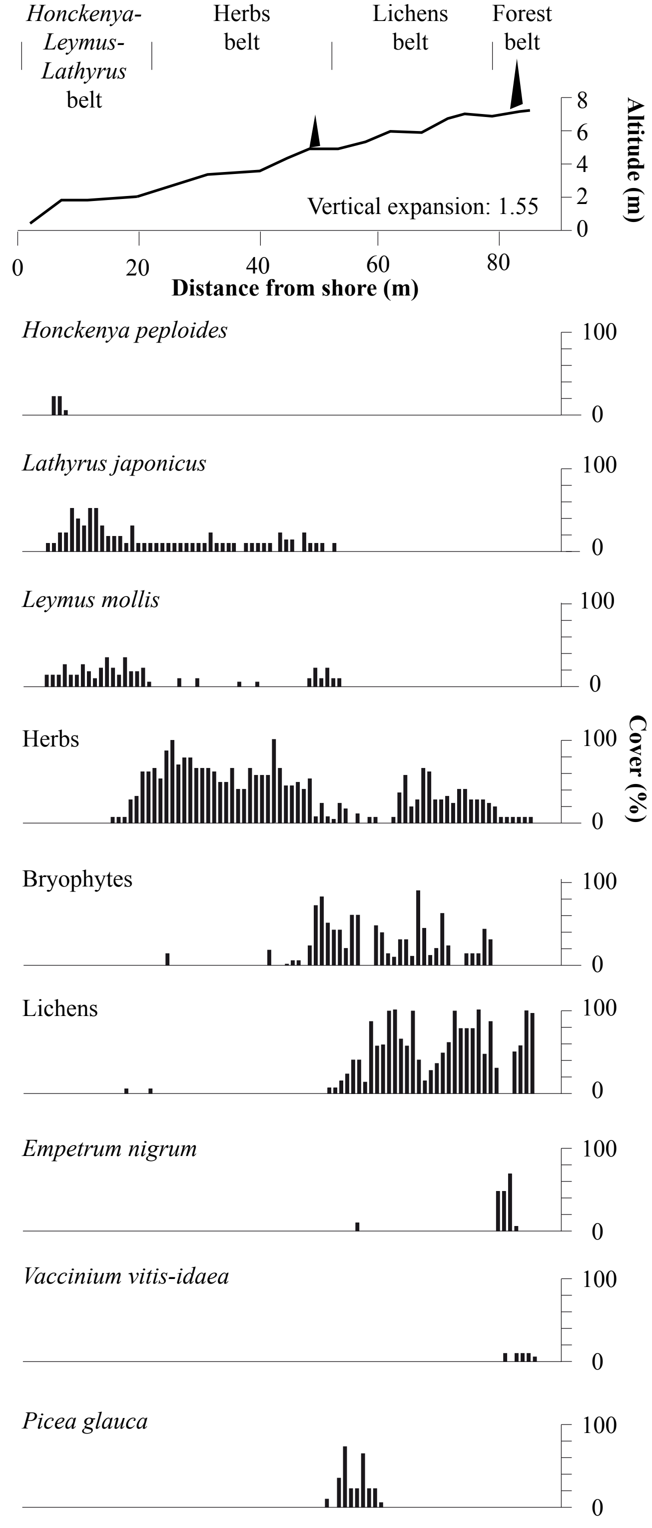

FIGURE 9. Primary succession of vegetation on the fast-rising coast in the Whapmagoostui-Kuujjuarapik area (Figure 1, site 18). Modified from Laliberté (2006).

More recent studies have been undertaken on the dune vegetation to examine the population dynamics of *Empetrum nigrum* L. (black crowberry). Analysis over a 6-ha grid at W-K showed that there had been effective seedling establishment for this species, which is believed to rely mainly on clonal growth to maintain its populations. As a result, *E. nigrum* showed a 200-m expansion towards the shoreline over the last 50 y, with evidence of ongoing expansion (Boudreau, Ropas & Harper, 2010).

Dynamics of peat ecosystems

Peatlands are widespread in the W-K region. They have developed on fine-grained material, specifically marine clays deposited in the deep waters of the Tyrrell Sea after deglaciation, about 8400 cal. y BP (Lajeunesse, 2008). In the W-K region, geomorphological and paleoecological aspects were studied of the Sasapimakwananisikw palsa peatland (Figure 2c), 8 km south of the village at an elevation of 110 m asl (Hamelin & Cailleux, 1968; Arlen-Pouliot, 2003; Arlen-Pouliot & Bhiry, 2005; Roy, 2007; Fillion, 2011; Hayes, 2011; Lamarre, 2011). The ecological and trophic evolution of the Kwakwatanikapistikw palsa peatland, 12 km east of the village (elevation: 95 m), was also reconstructed (Bhiry & Robert, 2006; Figure 1, site 21). Peat started to accumulate after the marine regression, about 6000–4700 cal. y BP (Arlen-Pouliot & Bhiry, 2005; Bhiry & Robert, 2006). Macrofossil data indicate that the first species to colonize wet sites were aquatic plants, chiefly Cyperaceae (Arlen-Pouliot & Bhiry, 2005; Bhiry & Robert, 2006). The macrofossil assemblages are consistent with those of a fen (Figure 10). At about 3100 cal. y BP, a decrease in peat accumulation rate, combined with the near disappearance of Cyperaceae and brown mosses, marked the transition to ombrotrophic conditions.

Ombrotrophication of the peatlands resulted from both autogenic (vegetation and hydrological changes) and allogenic factors created by a cooler climate during the Late Holocene (Filion, 1984a; Allard & Seguin, 1987; Payette & Filion, 1993b; Miousse, Bhiry & Lavoie, 2003; Arlen-Pouliot & Bhiry, 2005; Bhiry & Robert, 2006). In Nunavik, low temperatures and dry winter conditions after 500 BP favoured permafrost development, particularly in peatlands (Payette, 1984). Frost upheaval at the peat surface was responsible for the formation of palsas, small, round- or oval-shaped permafrost mounds (Payette, 1984).

Several studies showed that palsas, lithalsas, and permafrost plateaus in Nunavik formed recently, at the beginning of the Little Ice Age (Couillard & Payette, 1985; Allard, Seguin & Lévesque, 1986; Allard & Seguin, 1987; Gahé, Allard & Seguin, 1987; Lavoie & Payette, 1995; Allard & Rousseau, 1999; Payette & Delwaide, 2000; Beaulieu & Allard, 2003; Cyr & Payette, 2010). The tops of palsas are colonized by dwarf birch, ericaceous plants (*Vaccinium*, *Rhododendron*, and *Empetrum*), and lichens, in response to the better drainage conditions.

After the Little Ice Age, warming contributed to the formation of thermokarst ponds in palsa bogs of the W-K region and throughout Nunavik (Allard & Seguin, 1987; Laprise & Payette, 1988; Laberge & Payette, 1995; Payette *et al.*, 2004; Arlen-Pouliot & Bhiry, 2005; Vallée & Payette, 2007; Thibault & Payette, 2009). The brown/black-coloured thermokarst ponds in the Sasapimakwananisikw peat bog are colonized mostly by *Sphagnum*, *Carex*, and brown mosses (Arlen-Pouliot & Bhiry, 2005; Roy, 2007; Fillion, 2011). The differential development of 2 palsa fields belonging to the same peatland was attributed to geomorphological factors such as slope that control water flow (Fillion, 2011).

A paleoecological study of the Sasapimakwananisikw peatland based on isotopic analysis was undertaken by Hayes (2011). Analyses of δ^{18}O in the peat from 2 cores, which dated more than 5000 and 1370 cal. y BP, showed that changes corresponded to the main developmental stages of the peatland (succession from fen to bog to palsa), and to the associated hydrological conditions at the surface of the peatland. High isotopic values recorded during a short period between 4480 and 4340 cal. y BP were attributed to drier climate conditions (Hayes, 2011). A transfer function based on testate amoebae was developed to infer the past moisture conditions of the peat (Lamarre, 2011). Two cores were collected, at the central part and at the margin of the peatland. Differences recorded between the cores were likely due in part to autogenous factors controlling the dynamics of the peatland. However, hydrological events deduced from the central core were synchronous with lake-level fluctuations recorded in northern Quebec (*e.g.*, Payette & Filion, 1993b).

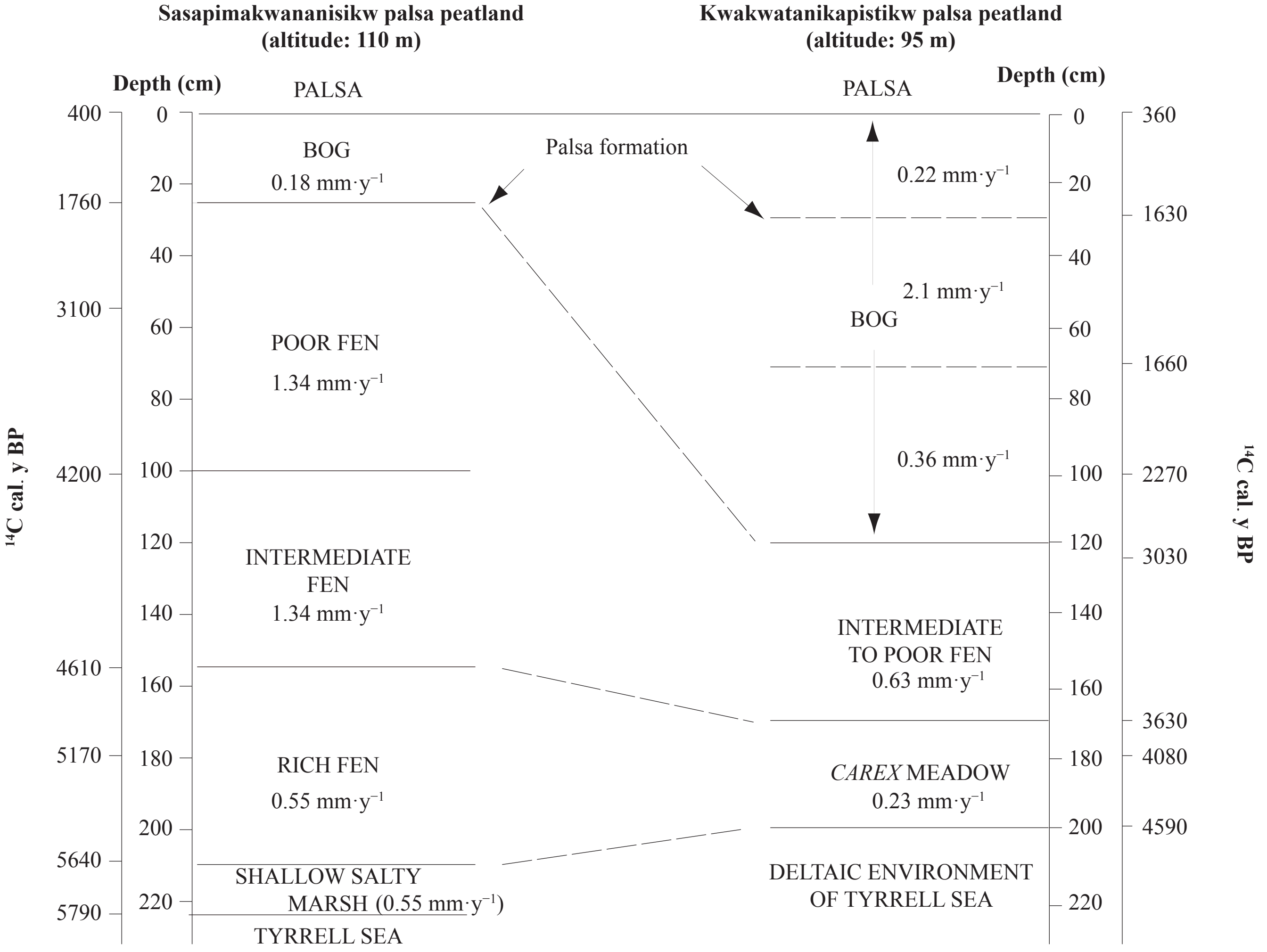

FIGURE 10. Paleoenvironmental records of succession in the Sasapimakwananisikw and Kwakwatanikapistikw peatlands. Modified from Bhiry and Robert (2006).

Insect populations

Entomological studies at W-K are still limited, but the studies to date provide species lists for a few specific groups that can be used as a baseline for detecting future change and the arrival of new taxa from the south. Surveys of diurnal butterflies in the region at many sites along the coast yielded a total of 24 species, with taxa belonging to the Nymphalidae (12 species), Lycaenidae (5 species), Satyridae (4 species), and Pieridae (3 species) families (Gauthier & Koponen, 1987; Koponen, 1994). The preferred habitats of most of these butterflies were wet sites, although some species preferred open and windy hilltop areas. Species belonging to the Noctuidae (owlet moths) family were also found (Koponen & Lafontaine, 1991). In total, 55 species were captured, 2 of which (*Discestra farnhami* Grote and *Lasionycta perplexa* Smith) were new records for the province of Quebec.

A quantitative analysis of larval mosquito populations (Diptera: Culicidae) was made by Maire and Bussières (1983). They found 17 species, of which the most common were *Aedes hexodontus* (in 60% of all samples), *A. punctor* (28%), *A. excrucians* (26%), *A. communis* (26%), *A. pullatus* (21%), and *A. pionips* (15%). Ponds on rock outcrops and thermokarst ponds were identified as the most propitious sites for the development of mosquitoes.

In a study of Coleopterans in the Dytiscidae family (predaceous diving beetles) conducted in the W-K region, Alarie and Maire (1991) identified 44 species belonging to 12 genera. These were mostly boreal species reflecting characteristic features of subarctic and arctic populations. A study encompassing several areas in the Nunavik region inventoried 6 ant species in the W-K region (Francoeur, 1983). *Leptothorax acervorum* was discovered at 4 sites in Nunavik (including W-K), and provided the first records of this species for North America.

Genetic studies have been undertaken on water striders (Insecta: Hemiptera: Gerridae) in the W-K area as part of a biogeographical study across North America (Gagnon & Turgeon, 2010). This work has shown the presence of 2 species around W-K: *Gerris buenoi* Kirkaldy, 1911 and *G. gillettei* (Lethierry & Severin, 1896). The latter species was a new record for eastern North America, suggesting a peculiar disjunct distribution of populations in western USA and Canada, on the one hand, and eastern Canada on the other. However, genetic comparisons with sister species revealed that *G. pingreensis* (Drake & Hottes, 1925) and *G. gilletei* should be synonymized as *G. gilletei*, a taxon of continent-wide distribution.

Human occupation

The first signs of human occupation in the W-K region date back to the Early Paleoeskimo. At one such site (GhGk-4, Figure 1, site 22), about 1.5 km northeast of the village, the earliest occupation was dated at 3800 BP (Institut culturel Avataq, 1992). This Early Pre-Dorset occupation is one of the oldest dated Paleoeskimo presences in Nunavik (Gendron & Pinard, 2000; Desrosiers & Rahmani, 2007). Another site (GhGk-63), about 1 km north of the village, was dated at between 1700 and 2000 BP. This site included 9 habitation structures, mainly tent rings. Excavations of 3 of these yielded a collection of 12 000 lithic artefacts associated with the Classic Dorset (Desrosiers & Gendron, 2004; Desrosiers, 2009).

According to the Hudson's Bay Company archives, the first recorded contact between Europeans and the Cree First Nation in the W-K region was in 1744 by an explorer working for this British company. An excerpt from the "Journal of Thomas Mitchell" (p. 34, July 25, 1744) reads, "a very fine river but very little wood to be seen. I had several of the natives on board…". The first Hudson's Bay Company trading post at the site, built in 1756, probably increased the frequency of visitors from the south, and was the precursor to the present W-K villages. The trading post was occupied sporadically until 1857, then continuously between 1857 and 1940. Hudson's Bay archives report that the Cree inhabited the region between June and August. Some Cree were employed by the company, including for hunting.

Towards the mid-1950s, a military airfield was built at W-K, which prompted Cree and Inuit families to settle nearby. Since then, the authorities have developed infrastructure providing the now sedentary population with access to lodging and services, including daily air connections to the south. In 1985, however, many Inuit families left Kuujjuarapik for the new village of Umiujaq, established 160 km further north along the coast. The 2006 census reported that there were 812 Cree living in the village of Whapmagoostui and 568 Inuit living immediately adjacent in Kuujjuarapik (Statistique Canada, 2007a,b).

Conclusion

The 5 decades of research described here have provided a solid foundation of knowledge concerning the Great Whale River region and its terrestrial geosystems and ecosystems. This area has proven to be an excellent site for analysis of plant succession, landscape evolution in response to deglaciation and uplift, permafrost and periglacial processes, and coastal geomorphology, including sand dune dynamics. A wide variety of paleoecological and paleoclimatological studies have been applied, including detailed paleolimnological analysis of coastal lakes. Peatland, soil, and vegetation studies have similarly revealed the long history of continuous change in the W-K region, from deglaciation to the present, with ongoing rapid uplift. Despite this diversity of research, there are some conspicuous gaps, including relatively little work on soils, birds, and mammals in the region. A small number of studies have taken place on insects, but this work is still in its infancy, as are process studies on soil dynamics, carbon fluxes, and land–water interactions.

The Great Whale River region is now entering a phase of rapid climate and landscape transition. As noted in this review, Hudson Bay has experienced the fastest rate of loss of sea ice of all sectors in the Canadian North over the last few decades. This has been accompanied by markedly warmer air temperatures at W-K that are unprecedented in the observational climate record, and perhaps without parallel for hundreds of years or longer. Historically, W-K has experienced several phases of rapid social and economic change, beginning with the arrival of the Hudson's Bay Company in the 18th century. The establishment of the military base at W-K in the 1950s continues to have a lasting impact on the vulnerable sand dune soils and vegetation, more than half a century later. This region is now undergoing a new phase of rapid economic development, with expansion of municipal services and infrastructure. In 2008, for example, W-K became fully serviced with a reticulated drinking water supply (from a groundwater source) and sewage reticulation and treatment. The Government of Quebec in its March 2011 budget specifically allocated $33 million to W-K to evaluate the feasibility of a deep-water port and a road link to southern Canada via Radisson, as a large-scale project within the "Plan Nord" to connect Nunavik with the rest of the world. The Great Whale River region is on the brink of major physical, ecological, social, and economic change, and there is a pressing need for ongoing multidisciplinary research that builds on the work conducted by CEN over the last 50 years.

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