

Early Wisconsinan (MIS 4) glaciation on Haida Gwaii, British Columbia, and implications for biological refugia

Rolf W. Mathewes, Olav B. Lian, John J. Clague, and Matthew J.W. Huntley

Abstract: Sea cliffs at Cape Ball on Graham Island, British Columbia, expose a thick sequence of Pleistocene sediments deposited during at least two glaciations. In sequence, from the base of the section, the units are (1) stony mud, (2) till, (3) silt, sand, and peat, (4) stony mud, (5) laminated sand and silt, (6) cross-bedded sand, and (7) till. Of special interest is unit 4, a massive to weakly stratified mud containing scattered stones that was deposited during the penultimate Pleistocene glaciation (marine isotope stage (MIS) 4). This unit contains wood and marine shell fragments that have yielded non-finite radiocarbon ages. Sand and silt with thin stringers of peat (unit 3) directly underlie this stony mud, and returned an optical age of 57.3 ± 5.7 ka. The stony mud is unconformably overlain by ponded sediments (unit 5) and advance outwash (unit 6) and till (unit 7) deposited during the Fraser Glaciation (MIS 2). The optically dated unit and a correlative peat and silty sand unit at a nearby exposure have pollen spectra with almost 100% non-arboreal pollen. Very low values of tree pollen, coupled with high frequencies of sedges, grasses, composites, Ericales, and the arctic-alpine indicator *Koenigia islandica*, indicate tundra vegetation and a cold climate. Abundant coprophilous *Sporormiella* (69%–91%) and *Sordaria* type (14%–47%) fungal spores in the peat samples indicate the former presence of grazing mammals at Cape Ball during MIS 4. During the MIS 3 interstadial, subalpine forest existed at low elevations on Graham Island, providing environments suitable for the development of genetically distinct bird and mammal populations that survived in lowland refugia during the Fraser Glaciation.

Résumé : Dans les falaises maritimes de l'île de Graham, Colombie-Britannique, affleure une épaisse séquence de sédiments, datant du Pléistocène, déposée durant au moins deux glaciations. En séquence, à partir de la base de la section, les unités sont : (1) une boue pierreuse, (2) un till, (3) du silt, du sable et de la tourbe, (4) une boue pierreuse, (5) du sable et du silt laminés, (6) du sable à stratification entrecroisée et (7) un till. L'unité 4 est d'un intérêt particulier, c'est une boue massive à faiblement stratifiée contenant des pierres épargnées qui a été déposée durant l'avant-dernière glaciation au Pléistocène (étage isotopique marin (MIS) 4). Cette unité contient du bois et des fragments de coquillages marins qui ont donné des âges 14C non significatifs. Du sable et du silt avec de minces filons de tourbe (unité 3) se trouvent directement sous cette boue pierreuse et ils ont donné un âge optique de 57.3 ± 5.7 ka. Des sédiments endigués (unité 5), une avancée de matériel fluvio-glaciaire (unité 6) et un till (unité 7), déposés durant la glaciation Fraser (MIS 2), reposent de manière discordante sur la boue pierreuse. L'unité datée optiquement ainsi qu'une unité corrélative de tourbe et de sable qui affleure à proximité contiennent un spectre de pollen dont le pollen est près de 100 % non arboricole. De très faibles valeurs de pollen arboricole, jumelées à des fréquences élevées de carex, d'herbes, de composites, d'Ericales et de l'indicateur arctique/alpin *Koenigia islandica* indiquent une végétation de toundra et un climat froid. D'abondantes spores fongiques de coprophiles, *Sporormiella* (69–91 %) et de type *Sordaria* (14–47 %) dans les échantillons de tourbe indiquent la présence antérieure de mammifères au pacage au cap Ball durant MIS 4. Durant l'interstade MIS 3, il existait une forêt subalpine à de basses altitudes sur l'île de Graham, fournissant des environnements qui étaient adéquats pour le développement de populations aviaires et mammifères génétiquement distinctes qui ont survécu dans les refuges des basses terres durant la glaciation Fraser. [Traduit par la Rédaction]

Introduction

Biologists and geologists have long debated the glacial history of Haida Gwaii (formerly Queen Charlotte Islands, Fig. 1). The focus of the debate has been on the origin of plant and animal endemics and range disjunctions (Calder and Taylor 1968; Sutherland Brown 1968; Clague et al. 1982; Heusser 1989; Ogilvie 1994; Shafer et al. 2010), and whether or not they record refugia and restricted Late Wisconsinan glaciation, which in British Columbia is referred to as the Fraser Glaciation (marine isotope stage (MIS) 2). The Fraser Glaciation began about 30 000 years ago and culminated about 16 000 years ago when an ice sheet covered nearly all of British Columbia (Clague 1981; Blaise et al. 1990; Porter and Swanson 1998).

In comparison, the ages and extents of the penultimate and older glaciations on Haida Gwaii are unknown, although they are beyond the limit of radiocarbon dating. Paleoenvironmental conditions associated with older glacial periods on Haida Gwaii are also unknown. In this paper, we use two approaches to determine the age and environment of the penultimate glaciation on Graham Island, the northern of the two main islands of the Haida Gwaii group. First, we review the stratigraphy and sedimentology of sediments exposed in sea cliffs at Cape Ball on the east side of Graham Island, within the boundaries of Naikoon Provincial Park (Figs. 1 and 2). These exposures were originally surveyed by Clague et al. (1982) and subsequently studied by Hicock and Fuller (1995). The current study was conducted near sites 16 and 17 of Clague

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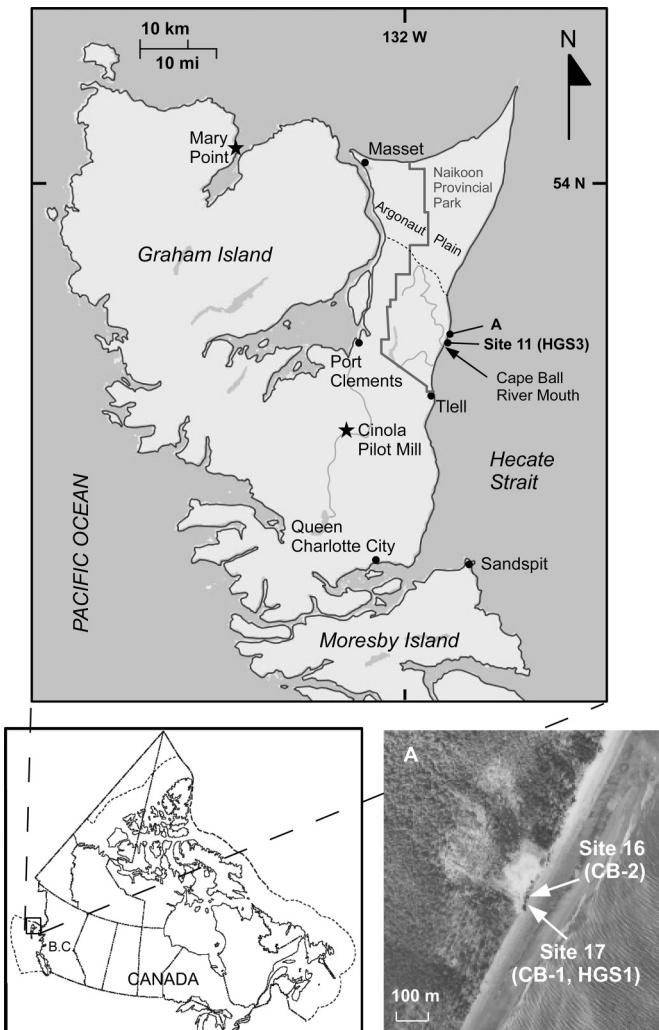
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R.W. Mathewes and M.J.W. Huntley. Department of Biological Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada.
O.B. Lian. Department of Geography and the Environment, University of the Fraser Valley, 33844 King Road, Abbotsford, BC V2S 7M8, Canada.

J.J. Clague. Department of Earth Sciences, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada.

Corresponding author: Rolf W. Mathewes (e-mail: mathewes@sfu.ca).

Fig. 1. Haida Gwaii location map and inset maps showing Cape Ball sample sites and other localities mentioned in the text. Inset map A shows the Cape Ball high sea cliff study area and the locations of optical dating sample HGS1 at site 17 of Clague et al. (1982) and pollen samples CB-1 and CB-2 at site 16. Optical dating site HGS3 is located at the mouth of Cape Ball River (site 11), about 2 km south of the main study area shown in inset A. Image from BC Air Photo 80008-171, taken in 1980.



et al. (1982), where the high sea cliffs extend more than 20 m above sea level (Figs. 1A and 2). We use the site numbers from Clague et al. (1982) in this report, along with new designations for optical dating samples and pollen diagrams. Second, we optically dated sediments (sample HBS1) that we associate stratigraphically with penultimate glaciation at site 17 of Clague et al. (1982) (Figs. 3 and 4). We also analyzed the optically dated sediments for pollen and spores at locality 17 (10 m north of HGS1 (sample CB-1, Fig. 3)), and at locality 16 of Clague et al. (1982) (a further 30 m north, which we sampled in 1986 (sample CB-2, Figs. 1 and 2)). Finally, we obtained an optical age on early Holocene sediments at site 11, located near the mouth of Cape Ball River about 2 km to the south of the main sea cliff site (Fig. 1). We optically dated sample HGS3 to test our protocol on a sample whose age has been well-defined by radiocarbon dating.

Palynology is a widely used tool to assess vegetation history and paleoclimate, and analyses of the Cape Ball sediments provide new paleoenvironmental data for the Early to Middle Wisconsinan, a poorly known interval in coastal British Columbia. The

only other locality on Haida Gwaii with sediments pre-dating the Last Glacial Maximum (LGM), that have also been paleoecologically studied, is the Cinola Pilot Mill site (Fig. 1) along the Yakoun River (Warner et al. 1984). At that site, a 55 cm thick peaty bed dated between $45\,000 \pm 970$ and $27\,500 \pm 400$ ^{14}C yr BP yielded pollen assemblages indicative of subalpine forest conditions.

Methods

Optical dating

We collected optical dating sample HGS1 from unit 3 at locality 17 of Clague et al. (1982) in the Cape Ball sea cliff (Figs. 1 and 3). The sample came from a bed of well-sorted, horizontally bedded, medium sand with minor silt, about 15 cm below a 5–10 cm thick peat bed near the centre of the unit (Fig. 3). We interpret the sand bed to be a low-energy fluvial deposit and therefore conducive to optical dating.

Optical dating is inherently experimental; the laboratory protocols used to determine an equivalent dose (D_e , see below) differ between minerals (typically quartz and feldspar), and can even differ regionally for a single mineral type. It is therefore prudent to test laboratory procedures each time they are applied for the first time at a particular site. We therefore collected a second optical dating sample (HGS3) from a low sea cliff near the mouth of Cape Ball River (Fig. 1; site 11 of Clague et al. 1982) to test our optical dating protocol on a sample of known age. This sample came from the centre of a 55 cm thick unit of massive silt and sand containing isolated pebbles, shells, and wood fragments. Clague et al. (1982) interpret this unit to be beach sediment. Six radiocarbon ages on shell and wood in this unit range from 8610 ± 80 ^{14}C yr BP (GSC-2738) to 9350 ± 80 ^{14}C yr BP (GSC-3120) (Clague et al. 1982). The calibrated 2σ age range for all six radiocarbon ages is 8336–10 183 cal yr BP (calibration was done using OxCal 4.2, IntCal and Marine 13 calibration curves, and a marine reservoir correction, ΔR , of 383 ± 172 yrs). The beach sediments are overlain by peat up to 1 m thick; a sample collected from the base of this peat at nearby site 9 of Clague et al. (1982) yielded a radiocarbon age of 5460 ± 70 ^{14}C yr BP (GSC-2963), or 6020–6405 cal yr BP.

Radiocarbon and optical dating provide different ages. The former is a measure of the time elapsed, in radiocarbon years BP, since the death of organisms associated with the sediment that enclose them, whereas the latter gives the time elapsed, in calendar years, since the last exposure of mineral grains in the unit to sunlight. On an active beach, mineral grains would be exposed to sunlight by reworking of the sediments due to wave action and burrowing organisms. In the case of a buried paleo-beach, which is the case here, an optical age would date the time of beach abandonment, when wave reworking and intertidal bioturbation ceased. In contrast, the age of the peat overlying the intertidal sediments at the mouth of Cape Ball River would be a minimum age for the active beach. The optical age for sample HGS3 should therefore lie between 6020 and 10 183 cal yr BP.

Since optical dating estimates the time elapsed since mineral grains were last exposed to sunlight, the method depends on the following: (i) measuring the rate at which radiation emitted during the decay of U, Th, and ^{40}K within the grains and from their surroundings, and cosmic rays, is absorbed by the mineral grains; and (ii) estimating the dose of radiation absorbed by the grains since they were last exposed to sunlight, which is referred to as the equivalent dose (D_e) (e.g., Lian and Roberts 2006; Wintle 2008; Lian 2013). In practice, D_e is found by observing how the luminescence intensity from a prepared sample of quartz or feldspar responds to increasing doses of laboratory radiation.

For this work, we dated K-feldspar. Quartz was found to be unsuitable because the intensity of the luminescence it emitted was low, and because the desired thermally stable ‘fast’ component of the signal was either absent or insignificant. For K-feldspar, we used the 4–11 μm fraction and the multiple-aliquot additive-

Fig. 2. Stratigraphy of Pleistocene sediments at site 16 in the Cape Ball sea cliff (see Fig. 1A for location). This exposure shows all described units except unit 1, which is covered by beach sediments. Unit numbers correspond to those in the text. CB-2 pollen samples were collected from unit 3 at this locality.

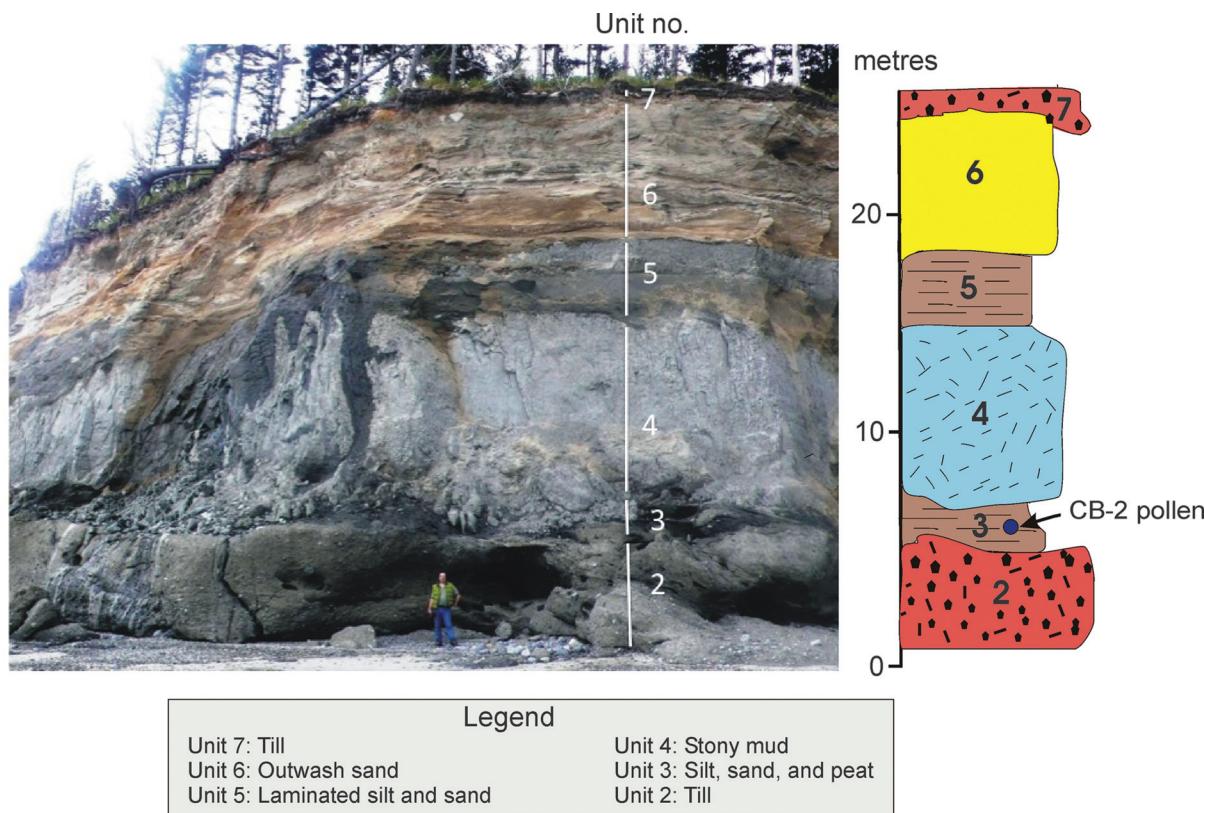
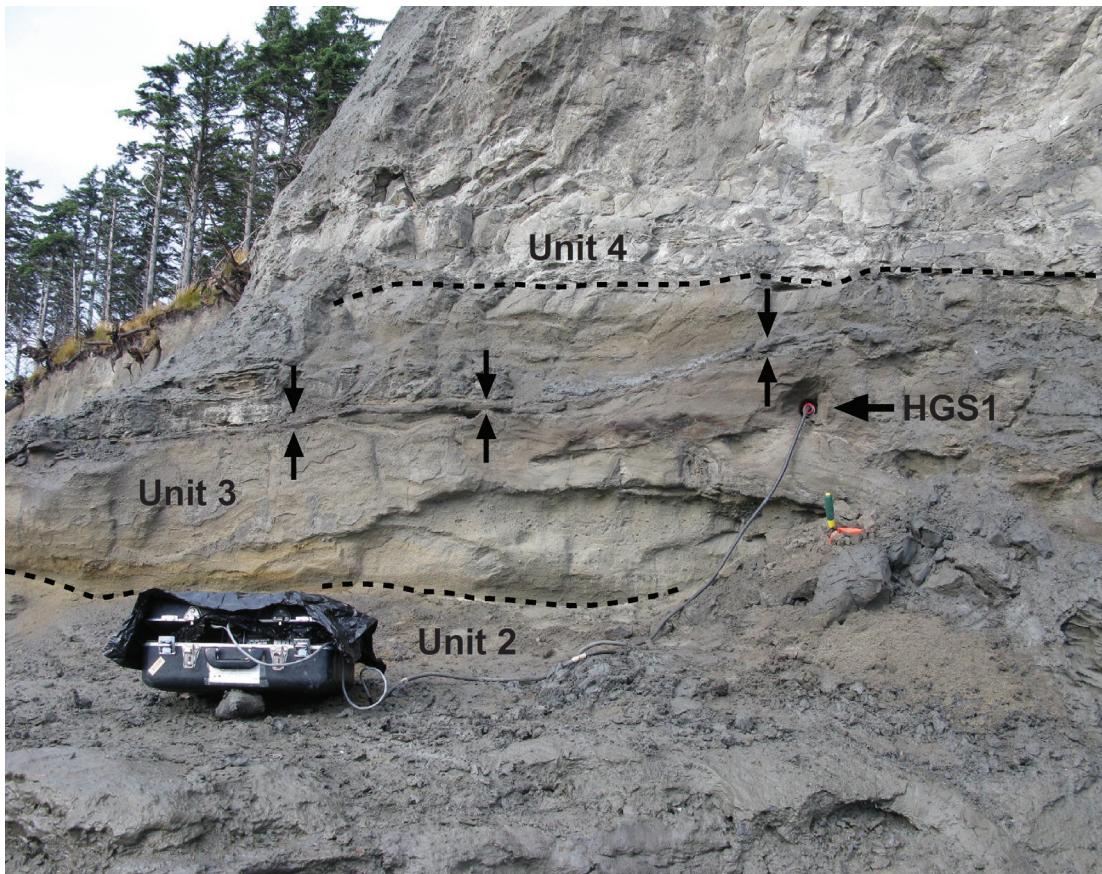


Fig. 3. Photograph showing unit 3 sediments at site 17, where optical dating sample HGS1 (see Fig. 4) and pollen sample CB-1 (right) were collected. The dark line is a shadow created by the overhanging peat bed.



Fig. 4. Photograph showing unit 3 in Cape Ball sea cliff and location where optical dating sample HGS1 was collected; a gamma spectrometer probe is inserted into the sediment. A thin compacted peat bed is located between the arrows and can be traced to where pollen samples CB-1 (Fig. 3) and CB-2 (Fig. 2) were collected.



dose with thermal transfer correction (ADTT) method (Huntley et al. 1993; cf. Lian and Roberts 2006) (Fig. 5). We chose this mineral species, the fine silt fraction, and the ADTT method because they have been used successfully to date similar deposits from a variety of sites in southern British Columbia, particularly for sediments ranging in age from near-modern to about 130 ka (Lian et al. 1995; Lian and Huntley 1999; Wolfe et al. 2008). Moreover, a benefit of using the fine silt size fraction is that anomalous fading, which refers to the unwanted loss of the thermally stable luminescence signal from laboratory-irradiated feldspar grains (Huntley and Lamothe 2001; Huntley and Lian 2006; Lamothe et al. 2012), can be low or negligible (Berger et al. 2004; Lian and Roberts 2006).

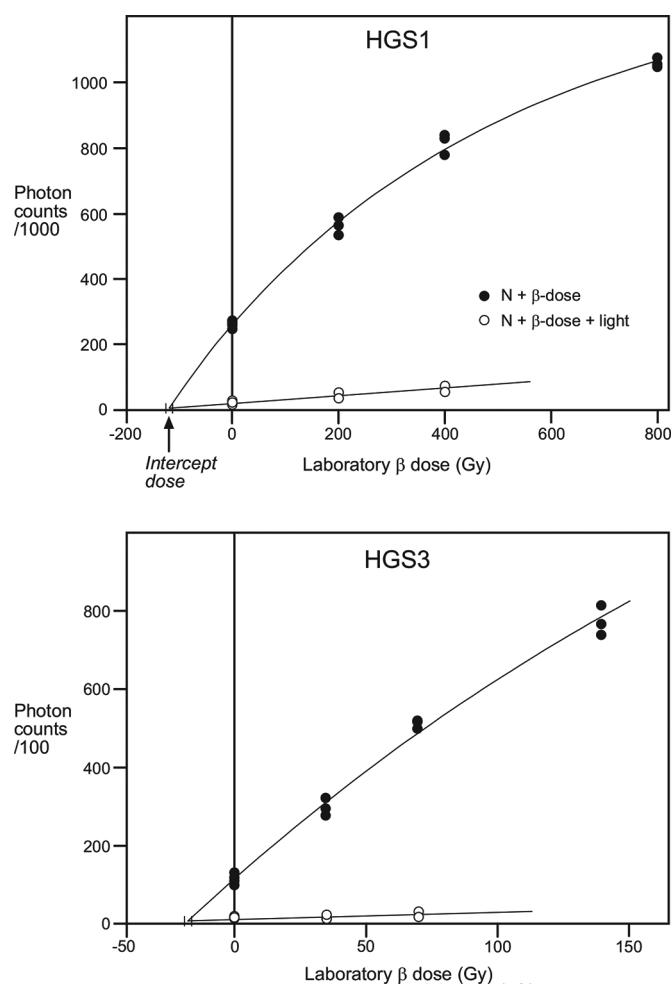
Palynology

In 2010, we collected seven samples for pollen analysis from the optically dated unit 3 sediments at site 17 at Cape Ball. Two samples were collected at optical dating sample site HGS1 and five more at pollen sampling site CB-1 (Fig. 3). After cleaning the section with shovel and trowel, we removed small blocks of ~100 mL of sediment with a knife, placed them in labeled plastic bags, and stored them at 4 °C until processed. Samples were selected to include peaty stringers to maximize pollen and spore recovery. A second exposure of unit 3 at site 16 of Clague et al. (1982), which is north of the optical dating site, was sampled for pollen in 1986. Three samples around a highly compacted, thin (2–3 cm) peat, previously radiocarbon dated at >51 ka (Table 1), and three sediment samples below this peat, were selected for comparison with the seven samples from the optical dating site. What is likely the same compacted peat was also sampled at the mouth of the Cape Ball River, where it is exposed during very low tides.

A representative subsample of 2–5 mL was taken from each sample by displacement in distilled water in a graduated 10 mL cylinder. Standard processing (Faegri et al. 1989) of the subsamples began with the addition of one or two tablets of *Eucalyptus* pollen (Batch 903722; 16 180 ± 1460 grains) to calculate pollen and spore concentrations. Each subsample was then digested in 10% HCl acid and 10% KOH, sieved through a 250 µm mesh screen, and treated with hot 48% HF acid to remove silicates. The Cape Ball samples were then given an acetolysis treatment to remove cellulose, dehydrated in an alcohol series, stained with safranin O, and the residues mounted in silicone oil and some also in glycerine jelly. We identified and counted pollen and spores at 400×–500× magnification using Zeiss and Nikon research microscopes; selected taxa were photographed under oil immersion (1000× magnification) using a Nikon Eclipse 80i with Nikon DS camera control (Nikon Instruments Inc., Melville, USA). Identifications were made using a pollen and spore reference collection at Simon Fraser University and standard keys (Faegri et al. 1989; Moore et al. 1991). Pollen sums used for percentage calculation include total terrestrial pollen. For spores and other palynomorphs, we used total pollen plus sums of other taxa. Calculation sums range from about 300 to 900 pollen grains. We generated pollen diagrams using Tilia software (Grimm 2011).

To look for macrofossils, we softened a sample of 500 mL of peaty sediment in KOH and wet-sieved it with 1 mm and 250 µm nested screens. Only broken and finely comminuted plant remains were found, without any identifiable seeds, wood, or leaf fragments. Further research using larger samples is needed to check for a macrofossil record at this site.

Fig. 5. Dose-response curves for samples HGS1 and HGS3 constructed using the first 5 s of excitation; curves were fitted to the data points using maximum likelihood statistics. Aliquots used to correct for the thermal transfer (lower curves) were given a 3 h infrared bleach using a quartz halogen lamp behind a Schott RG-715 optical filter (SCHOTT Gemtron Canada, Midland, Canada) that absorbs ultraviolet and most visible light. Before measurement, all aliquots were preheated for 4 h at 160 °C and then stored at room temperature for 30 days. For both samples, we fitted the additive-dose data with saturating exponential functions and the thermal transfer data with straight lines. For both samples, dose-intercepts were found to be constant with excitation time, thus the D_e s used for the age calculation were taken as the dose-intercept calculated using the luminescence integrated over the entire excitation time (100 s) after a correction for the decay that resulted from the normalization procedure (a “short shine” of 0.5 s). We made luminescence measurements using a Risø TL/OSL DA-20 reader (Risø National Laboratory, DTU Center for Nuclear Technology). Laboratory irradiations were applied with a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ β-source mounted on the reader that delivered $5.21 \pm 0.09 \text{ Gy} \cdot \text{min}^{-1}$ to fine silt ($4\text{--}11 \mu\text{m}$ diameter) grains mounted on an aluminum substrate. The K-feldspar fraction of the polymineral aliquots was stimulated preferentially using light-emitting diodes (LEDs) that delivered $20 \text{ mW} \cdot \text{cm}^{-2}$ of near-infrared ($\sim 880 \text{ nm}$, 1.4 eV) light to the sample. Violet luminescence ($\sim 400 \text{ nm}$, 3.1 eV) was detected by an Electron Tubes Ltd. 9235QB (ET Enterprises Ltd., Sweetwater, USA) photomultiplier tube placed behind a Schott BG-39 (SCHOTT Gemtron Canada) and Kopp 7-59 (Kopp Glass Inc., Pittsburgh, USA) optical filter. The BG-39 filter absorbs scattered infrared light from the LEDs, and the 7-59 filter absorbs yellow-green (570 nm, 2.2 eV) luminescence emitted from plagioclase feldspars.



Cape Ball stratigraphy and radiocarbon chronology

The northeast corner of Graham Island, which includes Cape Ball, is a triangular-shaped, low-lying plain (Argonaut Plain, Fig. 1) underlain by Pleistocene glaciogenic sediments. These sediments are well-exposed in the sea cliffs at Cape Ball where we recognize seven lithostratigraphic units (Fig. 2).

The lowest, occasionally exposed unit (unit 1) consists of up to 3 m of olive-gray stony clayey silt (hereafter termed ‘stony mud’) containing lenses of sand, up to 5%–10% stones, and rare fragments of marine mollusks. The stones include granitic and metamorphic lithologies derived from the British Columbia mainland to the east. Many of the stones are striated and faceted. The sediments are locally sheared, folded, and truncated by overlying unit 2. The origin of unit 1 is uncertain, although it is similar to the stony mud higher in the sequence (unit 4; see below). It is more than 51 000 ^{14}C years old, which is the same age as peat higher in the sediment sequence (Table 1). This unit is not shown in Fig. 2 because it is covered by beach deposits.

The next unit in the sequence (unit 2) is 1–3 m thick and consists of dense, olive-brown diamicton with a silt-sand matrix. Stones range up to boulder in size, constitute about 10%–20% of the sediment, and are dominantly volcanic and sedimentary lithologies of Haida Gwaii provenance; many are striated and faceted. The diamicton contains some deformed lenses of sand and minor gravel. Glacial flutings at the base of this diamicton trend at 45°. We interpret the diamicton to be a subglacial till, probably deposited by local Haida Gwaii glaciers. Unit 2 is older than the limit of radiocarbon dating, although one finite radiocarbon age (Table 1) has been reported. However, with non-finite ages both below and above unit 2, we consider this date to represent only a minimum age.

Up to 3 m of horizontally bedded sand and silt with thin, discontinuous layers of peat (unit 3) sharply overlies unit 2 till. Unit 3 is interpreted as representing a low energy fluvial environment, possibly with periodic shallow ponding. Radiocarbon ages obtained from the thickest peat are beyond the radiocarbon dating limit (Table 1). Optical dating sample HGS1, reported later in the paper, was obtained from this unit (Figs. 3 and 4).

The next unit in the sequence (unit 4) comprises up to 7 m of olive-gray, massive to stratified, matrix-supported stony mud. It sharply overlies unit 3 and contains lenses of silt and sand, and broken shells of marine mollusks and foraminifera tests. Stones constitute less than 5% of the sediment and include granitic and gneissic rocks derived from the British Columbia mainland to the east. Many of the stones are striated and faceted. Both Clague et al. (1982) and Hicock and Fuller (1995) interpret this unit to be glaciogenic, but their interpretations differ in detail. Clague et al. (1982) consider the unit to be glaciomarine, whereas Hicock and Fuller (1995) interpret it to be subglacial till. The lack of deformation structures within bedded sand and silt directly below the stony mud argue against a subglacial origin, but the fragmented moluscan valves suggest that the sediment was eroded from the floor of Hecate Strait. In view of its unconformable upper contact and the optical age of sand in unit 3 (discussed below), it is clear that unit 4 was deposited near the western margin of the Cordilleran Ice Sheet during a glaciation older than Fraser Glaciation.

Laminated and thin-bedded silt and sand up to 4 m thick (unit 5) unconformably overlie the unit 4 stony mud. These sediments contain pollen, spores, and terrestrial and aquatic plant macrofossils that accumulated in shallow ponds, probably near sea level. AMS radiocarbon ages on plant macrofossils from this unit range from about 23 000 to 28 000 ^{14}C yr BP (Table 1). The sediments fill shallow basins or broad channels cut into unit 4, and were deposited when the Cordilleran Ice Sheet advanced toward Cape Ball early during the Fraser Glaciation (Clague et al. 1982).

The next unit in the succession (unit 6) conformably overlies units 4 and 5, and comprises up to 15 m of well-sorted, horizontally stratified sand with lenses of gravel and interbeds of clayey

Table 1. Radiocarbon ages from Cape Ball sea cliff section.

Age (^{14}C yr BP) ^a	Laboratory ^b	Material dated	Stratigraphic unit
23 200±280	RIDDL-481	Plant fragments	5
23 900±260	RIDDL-327	Moss (<i>Racomitrium canescens</i>)	5
23 900±1200	RIDDL-873	Moss (<i>Phlomotis fontana</i>)	5
25 400±1000	RIDDL-347	Moss (<i>Racomitrium canescens</i>)	5
25 800±280	RIDDL-483	Wood fragment	5
26 650±390	RIDDL-484	Twig (<i>Salix</i> sp.)	5
27 800+2100–1600	RIDDL-348	Beetle (cf. <i>Lepidophorus</i>)	5
27 900+2600–2000	RIDDL-349	Moss (<i>Racomitrium canescens</i>)	5
29 300+12 900–4700	RIDDL-346	Moss (<i>Racomitrium canescens</i>)	5
40 640±770 ^c	TO-391	Marine shell fragment	4
42 100±400 ^c	RIDDL-350	Marine shell fragment	4
>43 500	Beta-256110	Wood fragment	4
>43 500	Beta-256111	Wood fragment	4
>33 000	GSC-3208 ^d	Peat	3
>43 000	GSC-3207 ^d	Peat	3
>51 000	GSC-3207-2 HP ^d	Peat	3
>37 000	RIDDL-482	Wood fragments	2
36 700±1060 ^c	GSC-3242	Wood fragment (<i>Tsuga</i> sp.)	2
>40 000	GSC-3232	Wood fragment (<i>Picea</i> sp.)	1

^aErrors are $\pm 1\sigma$; GSC ages are reported at $\pm 2\sigma$.^bLaboratories: Beta, Beta Analytic Inc. (Florida); GSC, Geological Survey of Canada (Ottawa); RIDDL, Radio-Isotope Direct Detection Laboratory (McMaster University); TO, IsoTrace Laboratory (University of Toronto).^cShould be considered a minimum age.^dGSC-3208 (>33 000), GSC-3207 (>43 000), and GSC-3207-2 (>51 000) are ages determined for the same sample. GSC-3207 and GSC-3207-2 were determined on the less soluble fraction pretreated with NaOH, HCl, and distilled water; the former is based on one 3-day count in the 2 L counter, and the latter one 5-day count in the 5 L counter at high pressure. GSC-3208 was determined from the more soluble fraction (filtrate from GSC-3207 acidified after base treatment, and the resulting precipitate washed, dried, and burned). GSC-3207-2 supersedes GSC-3207.

and sandy silt. The sand consists mainly of quartz, feldspar, and lithic grains derived from granitic and gneissic rocks that dominate the Coast Mountains to the east. Cross-beds within the sand indicate deposition by southerly and southwesterly flowing streams. Clague et al. (1982) interpreted the sand to be outwash deposited in fans in front of the Hecate lobe of the Cordilleran Ice Sheet as it approached Graham Island immediately before the LGM. It resembles Quadra Sand, a widespread unit of advance outwash deposited in south-coastal British Columbia during the early stages of the Fraser Glaciation (Clague 1976, 1977).

The uppermost unit (unit 7) in the Cape Ball sea cliff is discontinuous, less than 2 m thick, and comprises massive to stratified diamicton with striated and faceted stones up to boulder size. The stones are dominantly volcanic and sedimentary lithologies of Haida Gwaii provenance. At the west side of the Argonaut Plain, the ground surface is marked by long, low ridges oriented in a northwest–northeast direction (Sutherland Brown 1968; Clague et al. 1982). Sutherland Brown (1968) interpreted these features to be glacial flutings oriented parallel to the direction of ice flow that formed when ice flowing from the mountains on Graham Island coalesced with, and was deflected northward by, the Hecate lobe of the Cordilleran Ice Sheet. At that time—the peak of the last (Fraser) Glaciation—the Argonaut Plain was an interlobate area between the western margin of the Cordilleran Ice Sheet and local Haida Gwaii glaciers. We thus interpret unit 7 diamicton to be till of Fraser Glaciation (LGM) age.

Optical ages

Additive-dose curves for samples HGS1 and HGS3 are shown in Fig. 5, and dosimetry information, dose rates, equivalent doses, and optical ages are presented in Tables 2 and 3 (all error values are $\pm 1\sigma$). The optical age for sample HGS3 is 7.68 ± 0.58 ka, which is consistent with the expected age range of the unit based on radiocarbon dating (ca. 6000–10 200 cal yr BP). However, if the

Table 2. Sample depths, concentrations of relevant radioisotopes used for dosimetry, and in situ γ dose rates.

Sample name	<i>d</i> (cm) ^a	K (%)	Th ($\mu\text{g}\cdot\text{g}^{-1}$) ^b	U ($\mu\text{g}\cdot\text{g}^{-1}$) ^b	γ dose rate ($\text{Gy}\cdot\text{ka}^{-1}$) ^c
HGS1	550	1.21±0.03	2.49±0.21	1.36±0.14	0.566±0.020
HGS3	150	1.22±0.03	3.57±0.23	1.56±0.15	0.641±0.022

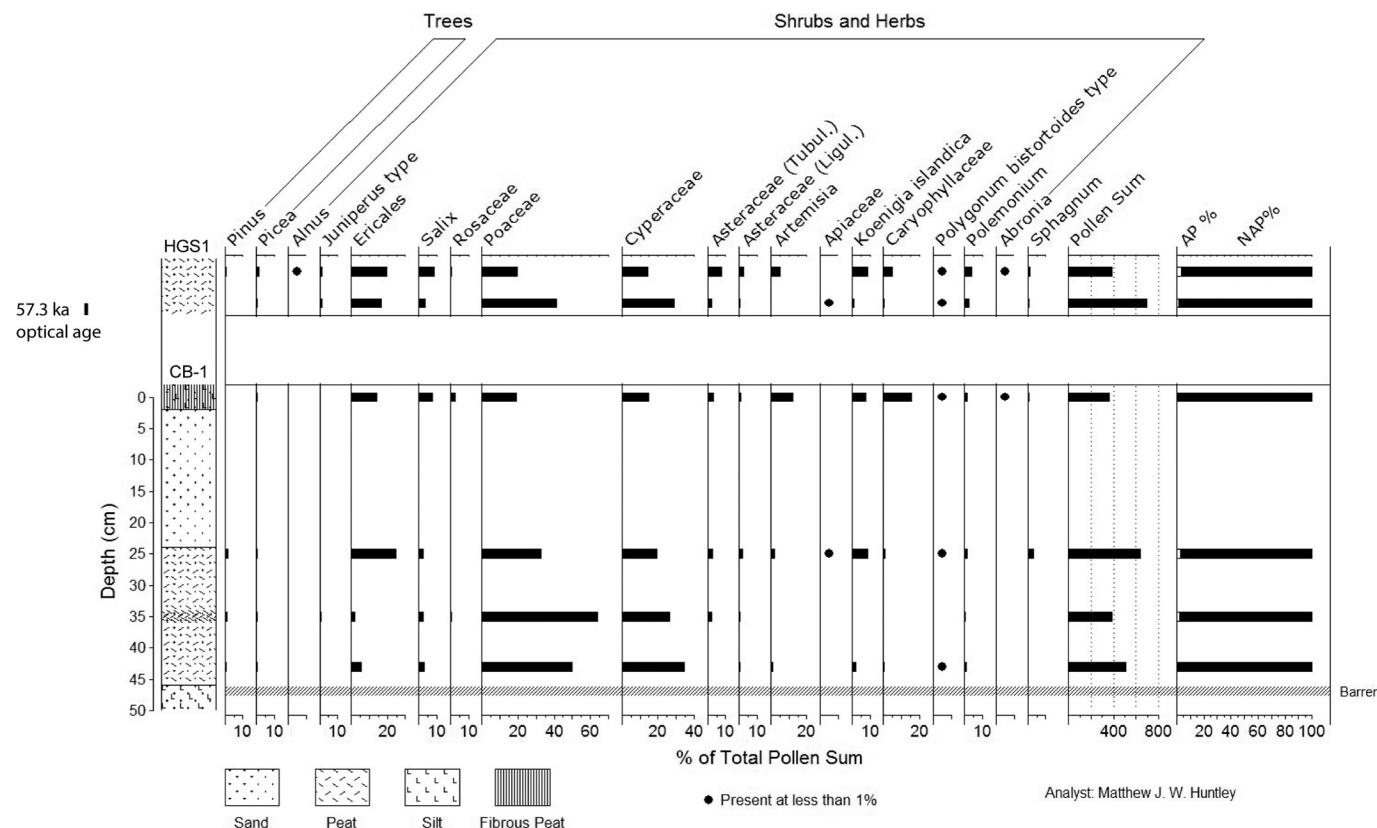
^aDepth of the sample beneath the ground surface.^bEquivalent concentrations calculated from the activities of ^{214}Bi for U and ^{208}Tl for Th, using in situ γ -ray spectrometry, assuming secular equilibrium. Note: The values shown are from in situ γ -ray spectrometry and have not been corrected for the presence of water; thus they are smaller than those that would have been calculated if the sediments were dry.^cFrom counts in the energy range 0.8–2.6 MeV, corrected for relative proportions of K, U, and Th.**Table 3.** Equivalent doses (D_e), dose rates, and optical ages.

Sample	D_e (Gy)	\dot{D}_c ($\text{Gy}\cdot\text{ka}^{-1}$) ^a	\dot{D}_T ($\text{Gy}\cdot\text{ka}^{-1}$) ^b	Age (ka)	Corrected age (ka) ^c
HGS1	69.3±4.6	0.088±0.004	2.23±0.19	31.1±3.4	57.3±5.7
HGS3	19.5±0.8	0.162±0.008	2.54±0.16	7.68±0.58	8.71±0.67

^a \dot{D}_c dose rate due to cosmic rays (Prescott and Hutton 1994).^b \dot{D}_T total dose rate (that due to cosmic rays plus that due to γ , β , and α radiation). Note: For each sample the alpha efficiency (*b* value) was estimated to be $1.0 \pm 0.1 \text{ Gy}\cdot\mu\text{m}^2$. As-collected water contents were assumed for each sample.^cOptical age for samples HGS1 and HGS3 corrected for anomalous fading using the methods of Huntley and Lamothe (2001) and Lamothe et al. (2003), respectively. See the text for the fading rates.

fossil shells in the beach deposit (ca. 8300–10 200 cal yr BP) more closely date the abandonment of the beach than does the radiocarbon age from base of the overlying peat, then the optical age may be too young, possibly due to anomalous fading. To check for the presence of significant anomalous fading, we estimated the

Fig. 6. Pollen percentage diagrams for samples collected from unit 3 at Cape Ball (site 17; Fig. 3). Note that the pollen percentages from the samples collected at the location of optical dating sample HGS1 are plotted above those from pollen sample CB-1. The thin peat bed that occurs directly above the location of sample HGS1 (see Fig. 4) is not shown in this diagram.



fading rate (g) for sample HGS3 using the single-aliquot regenerative-dose (SAR) method of Auclair et al. (2003). Based on 12 aliquots, g was found to be $2.5\% \pm 0.1\%$ per decade, which leads to a fading-corrected optical age of 8.71 ± 0.67 ka using the correction method of Huntley and Lamothe (2001), which is applicable for samples, such as this one, whose natural luminescence lies within the linear part of its dose-response curve. This age is consistent with the age range of fossil shells dated in the unit, and with the age range obtained if the age of the base of the overlying peat is included, and thus gives us confidence that our dating protocol is correct.

Sample HGS1 yielded an optical age of 32.3 ± 3.5 ka and a fading rate of $5.5\% \pm 0.5\%$ per decade; the corrected age is 47.0 ± 5.7 ka using the method of Huntley and Lamothe (2001). However, since the luminescence measured from natural aliquots of this sample falls within a part of its dose-response curve that may not be sufficiently linear for this method to be applied, we also used the dose-response correction (DRC) method of Lamothe et al. (2003), which apparently does not suffer from this limitation. This method yielded an optical age of 57.3 ± 5.7 ka.

An optical age can be too old if a significant number of the grains sampled were not exposed to sufficient sunlight prior to burial. Insufficient exposure of grains to sunlight was likely minimal for sample HGS1 because of the depositional conditions (a low-energy fluvial environment that allowed peat to develop), and because its optical age is supported by a radiocarbon age (>51 ka BP; GSC-3207-2, Table 1) that was obtained using the “high pressure” radiometric method. This long-count radiocarbon dating method has provided “finite” ages up to about 54 ka BP (Lowdon 1985). A K-feldspar optical age could be too young if the method used to correct for anomalous fading is not applicable. The DRC method used to correct sample HGS1 for this effect is still novel and it has

not been widely tested, and for that reason the corrected age for HGS1 should be considered with some caution. However, recent work by Jensen et al. (2011) has shown consistency between a DRC-corrected optical age of ~ 106 ka from loess and independent age information.

Palynology

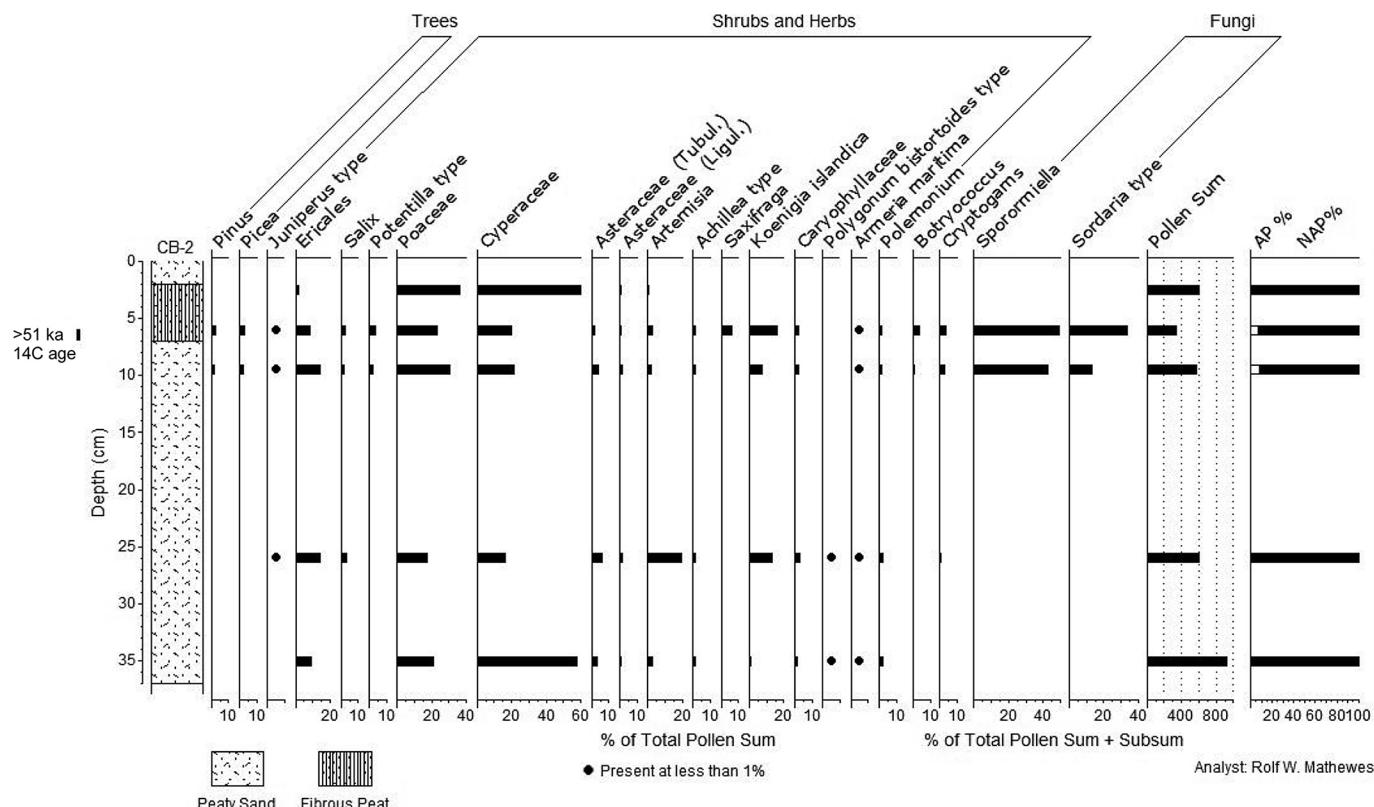
Two pollen diagrams (Figs. 6 and 7) summarize the main pollen and spore taxa as relative percentages. Pollen and spore preservation in most samples was good, allowing us to identify rare plant genera and some species in addition to Poaceae (grass), Cyperaceae (sedges), and Asteraceae (composites) at the family level. With one exception, concentrations range from 26 000 to 249 000 grains per mL of sediment, allowing significant pollen sums to be analyzed. Only one of the samples (CB-1) at the site where optical dating sample HGS1 was collected was considered barren, with extremely low pollen concentrations. We could not calculate pollen accumulation rates or influx values since sedimentation rates are not known. Images of both common and rare palynomorphs of particular interest (Figs. 8 and 9) from both samples CB-1 and CB-2 are illustrated and discussed below.

Discussion and conclusions

Glacial chronology

The extent of glaciation during MIS 4 in northwest North America has been long debated. Most researchers working in British Columbia have argued that the penultimate period of ice-sheet glaciation occurred at this time (e.g., Fulton 1971; Fulton and Smith 1978; Clague 1981), whereas different opinions have been voiced by researchers in the Yukon and Alaska. Early work from the Yukon and Alaska (Bostock 1966; Hughes et al. 1969) assigned

Fig. 7. Pollen percentage diagram for sample CB-2, which was collected approximately 30 m north of sample CB-1 (Fig. 2). The high values of coprophilous fungal spores were unexpected and indicate the local presence of grazing mammals.



the penultimate expansion of the Cordilleran Ice Sheet to the Early Wisconsinan (MIS 4) based on non-finite radiocarbon ages on sediments above penultimate (Reid) glacial deposits and correlation with classical midwestern United States stratigraphy. Later, Foscolos et al. (1977), Tarnocai et al. (1985), and Smith et al. (1986) described an interglacial soil, presumed to be of MIS 5e age, on Reid-age glacial sediments in central Yukon Territory, implying a MIS 6 age for the drift. Non-glacial sediments filling a gully incised into Reid-age outwash along the Stewart River in east-central Yukon contain a tephra that Westgate et al. (2001) correlated with the Sheep Creek tephra exposed at Fairbanks, Alaska. Berger et al. (1996) reported a thermoluminescence age of 190 ± 20 ka on the Sheep Creek tephra, leading Westgate et al. (2001) to infer a MIS 8 age for the Reid outwash at Stewart River. Thus, until recently, most researchers concluded that the penultimate (Reid) glaciation in the Yukon occurred during MIS 6 or 8 (Duk-Rodkin 1999; Westgate et al. 2001, 2005; Huscroft et al. 2004).

Ward et al. (2007), however, have argued that the penultimate drift sheet in the Yukon is not all the same age. It appears to date to MIS 6 in east-central Yukon, but is likely MIS 4 in southwest Yukon. This conclusion is based on detailed terrestrial cosmogenic nuclide (TCN) dating of large glacial erratics lying outside the MIS 2 (McConnell) glacial limit in the Aishihik River area. Their four TCN ages range from 51.2 ± 3.1 to 54.3 ± 2.0 ka. The erratics and associated drift were deposited by glaciers that flowed up to 300 km from an ice dome situated over the northern Coast Mountains in British Columbia. The source area for this ice is higher and more extensively glacierized today than the Coast Mountains east of Haida Gwaii, about 700 km to the south; nevertheless, it is reasonable to assume that an ice cap covered the latter area at this time and discharged glaciers towards Cape Ball, only 200 km to the west.

Briner et al. (2005) concluded that glaciers in several areas of Alaska reached their maximum penultimate extents during MIS 4.

They attributed extensive glaciation at this time to enhanced moisture availability at the MIS 4/3 transition, likely due to relatively higher eustatic sea levels than during MIS 2 and MIS 6. When sea levels were at their lowest positions during MIS 2 and MIS 6, vast areas of the continental shelf in the Bering Sea were exposed land, increasing the continentality of the interior regions of Beringia (Brigham-Grette et al. 2001). The increased continentality may have limited moisture availability, thus reducing the extent of glaciation compared to times when sea level was higher.

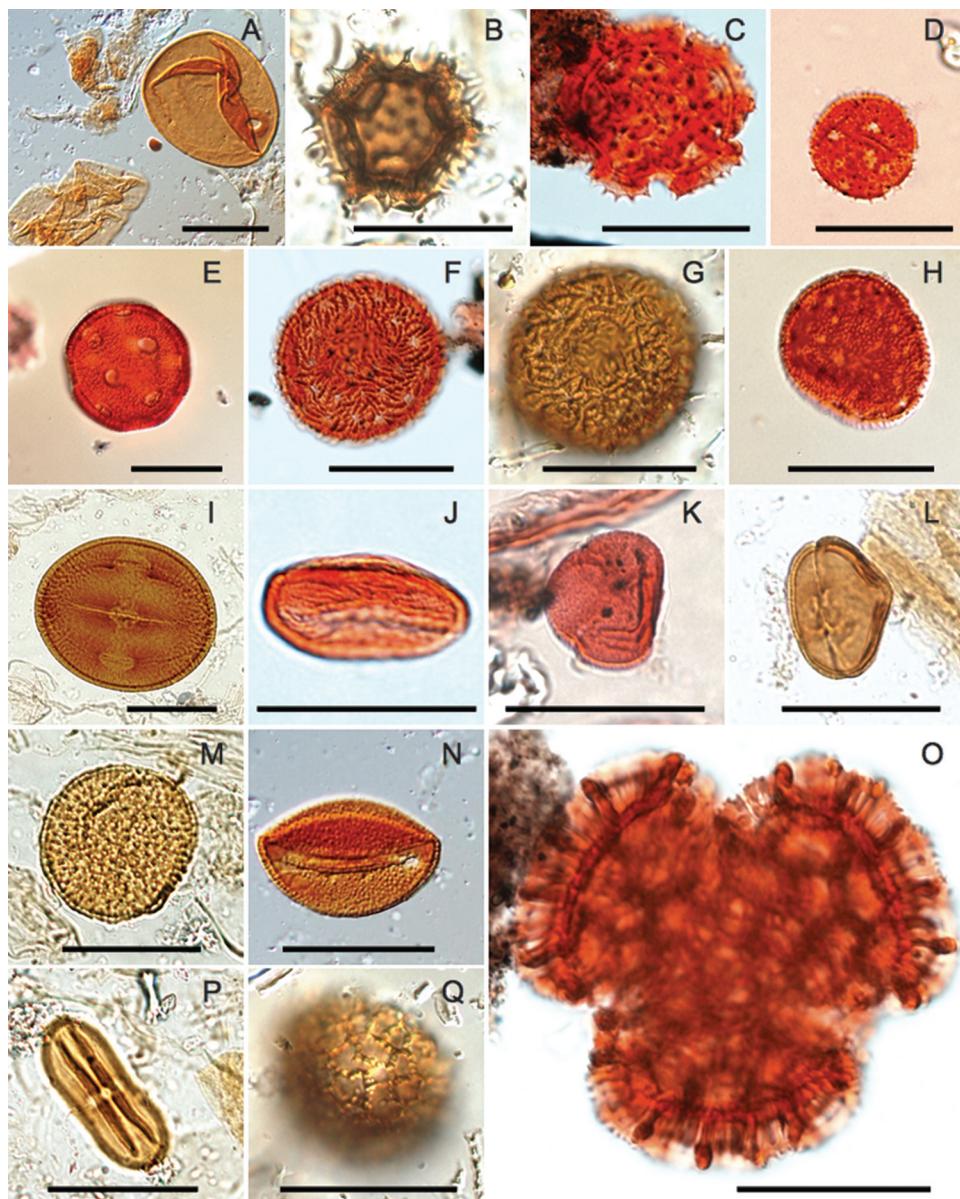
Palynology and paleoecology

Pollen record

The most striking feature of the pollen diagrams from the two sample sites is the scarcity of tree pollen. At the site of optical dating sample HGS1 (Fig. 3, CB-1 locality), tree pollen is less than 4% in all six samples and near 0% in some (Fig. 6). At pollen locality CB-2 (Fig. 2), two samples contain up to 8% total tree pollen, but the two basal samples have <1% tree pollen (Fig. 7). Dominance of non-arbooreal pollen (NAP), especially sedges (Cyperaceae) and grasses (Poaceae, Fig. 8A), as well as Ericales (heath shrubs, probably mostly *Empetrum*) at Cape Ball contrasts with the abundance of arboreal pollen at the mid-Wisconsinan Cinola Pilot Mill site (Warner et al. 1984). At the latter site, however, there is an increase of NAP at the base of the record, before $45\,700 \pm 970$ ^{14}C yr BP (GSC-3534-2). Cape Ball thus was likely a treeless tundra-like landscape 57.3 ± 5.7 ka ago.

Interpretation of very low tree pollen frequencies such as these can be contentious (Hicks 2006) and—in the absence of tree macrofossils or stomata—such low values are often interpreted as resulting from long distance pollen transport or from reworking of older sediments. Heusser (1989) suggested that low percentages of conifer and alder pollen at early postglacial sites such as Cape Ball around 15 ka could indicate survival of small colonies of

Fig. 8. Plate of selected pollen grains from unit 3 at Cape Ball. Black scale bars are 30 μm long. Photos taken at 1000 \times magnification with oil immersion; A, G, N, and Q were photographed under Nomarski interference optics; all others were photographed under brightfield illumination. (A) Poaceae with annulate pore at right, Cyperaceae lower left. (B) *Hieracium/Crepis* (Liguliflorae) with long spines. (C) *Taraxacum ceratophorum* type with short spines. (D) *Koenigia islandica*. (E) Caryophyllaceae. (F) *Polemonium occidentale* type with striato-rugulate ornamentation. (G) *Polemonium acutiflorum* showing rugulate ornamentation. (H) *Polemonium pulcherrimum* type. (I) *Polygonum bistorta* type, likely *P. viviparum*. (J) *Saxifraga oppositifolia* tricolpate striate type. (K) *Oxyria/Rumex* type; small size suggests likely *Oxyria* (mountain sorrel). (L) *Ligusticum calderi*, a former Haida Gwaii endemic. (M) Ranunculus (buttercup) pollen. (N) *Saxifraga hirculus* type, indicator of wet arctic–alpine sites. (O) Large pollen of thrift (*Armeria maritima*), a coastal indicator. (P) *Angelica genuflexa*, another coastal indicator. (Q) Rare pollen of sand dune-colonizing *Abronia*.

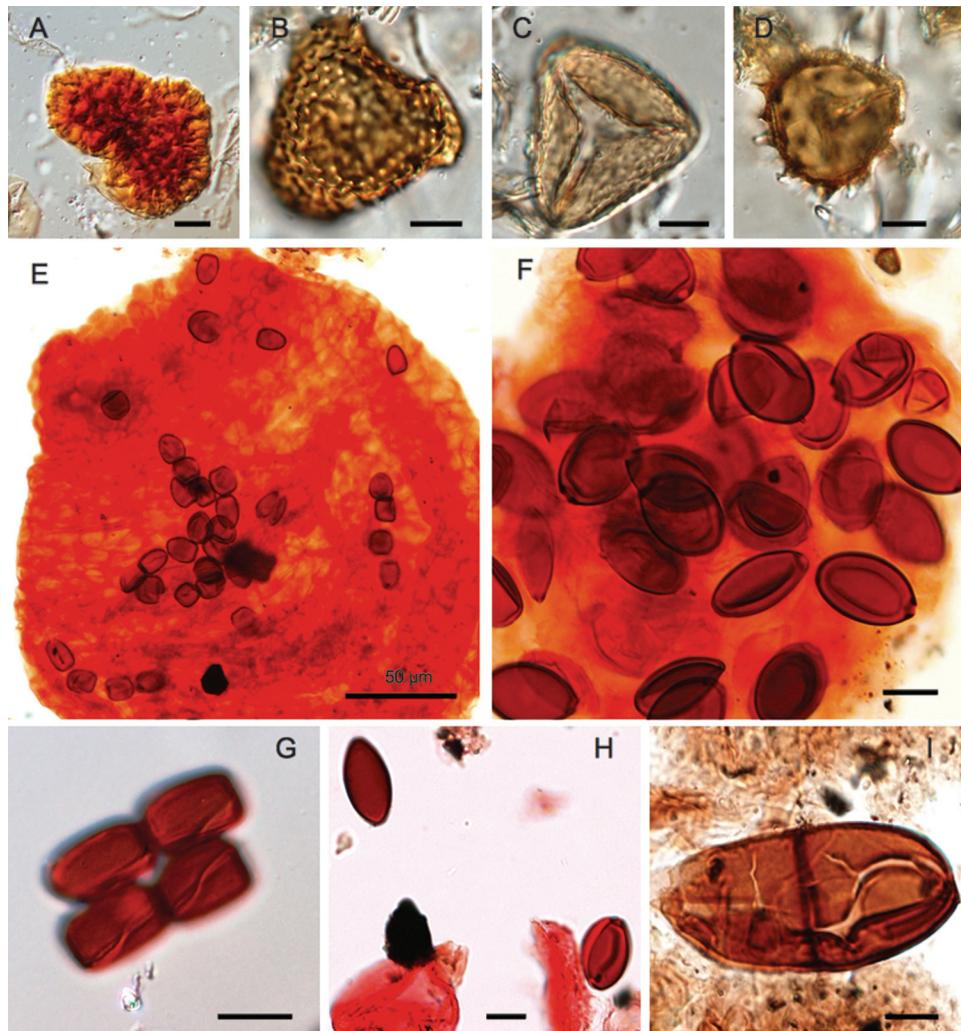


arboreal taxa in a tundra landscape. The trace amounts of tree pollen at our sea cliff pollen sites favour essentially treeless conditions during MIS 4, especially when viewed in light of the abundant arctic–alpine pollen indicator taxa. The single sample collected from peat at the mouth of Cape Ball River shows the same pattern, with dominance of Cyperaceae (59%) and Poaceae (26%), and total NAP of 99%. As Hicks (2006) notes, pollen accumulation rates would help to interpret whether or not some trees were present within the pollen catchment. Without knowing sedimentation rates, however, this is impossible at Cape Ball.

Most arctic–alpine indicator pollen types at Cape Ball are rare or present at frequencies of less than 5%, but they still convey important paleoecological information because they are mostly insect-

pollinated and indicative of local rather than regional environments. For example, Asteraceae (Liguliflorae), including *Hieracium* type and *Taraxacum ceratophorum* type (Figs. 8B and 8C), are present in open environments on Haida Gwaii today. *Koenigia islandica* (Fig. 8D) is a small herb of open arctic and alpine environments (Klinka et al. 1989) that is absent from the present flora, but was formerly a major element of periglacial environments. At our sites, it has unusually high pollen frequencies (up to 16%) and is present in every sample, indicating an open, cold, and wet local environment. The weedy Caryophyllaceae family of herbs (Fig. 8E) is likewise common in some samples (up to 5%), although absent in others. These herbs are generally indicators of open ground, but genera or species cannot be confirmed from their pollen. Of partic-

Fig. 9. Plate of selected non-pollen palynomorphs from Cape Ball site 16, locality CB-2 (Fig. 2). Images taken at 1000 \times magnification; A–D were photographed under Nomarski interference optics; all others were photographed under brightfield. Black scale bars are 10 μm long, except that for E, which is 50 μm long. (A) *Botryococcus* aquatic algal colony. (B) *Huperzia* foveolate spore. (C) *Botrychium*. (D) *Selaginella selaginoides*. (E) Fruiting body of coprophilous *Sporormiella* type with enclosed ascospores. (F) Fruitification of *Sordaria* type containing monoporate ascospores. (G) Detail of joined *Sporormiella* spores, showing the distinctive sigmoid apertures. (H) Two dispersed *Sordaria* type spores. (I) Large septate spore of *Amium* type.



ular interest are three morphotypes of Jacob's ladder (*Polemonium*) pollen at Cape Ball. This distinctive pollen genus is commonly present in late-glacial sediments and includes species occupying semi-desert to boreal and arctic-alpine environments, with subtle variations in pollen morphology (Mathewes 1979). Two species in our pollen assemblages (*P. occidentale* and *P. acutiflorum*) no longer occur on Haida Gwaii, and the third (*P. pulcherrimum*) is very rare at two localities. *Polemonium occidentale* type (Fig. 8F) and *P. acutiflorum* (Fig. 8G) typically grow in moist to wet soils in boreal meadows and tundra. Other presently rare, high-elevation species on Haida Gwaii include *Polygonum bistorta* type (likely *P. viviparum*) (Fig. 8I), *Saxifraga oppositifolia* type (Fig. 8J), *Oxyria/Rumex* type (Fig. 8K), and the former endemic *Ligusticum calderi* (Fig. 8L). The presence of *L. calderi* (Hebda 1985) confirms that some former endemic plants have had a long history on Haida Gwaii. Buttercups (*Ranunculus*) (Fig. 8M) are another common genus of open habitats, and a pollen grain of *Saxifraga hirculus* type (Fig. 8N) indicates an arctic-alpine taxon of very wet sites not found on Haida Gwaii today. It is rare in northernmost British Columbia, but circumboreal in subarctic and arctic environments.

Three pollen taxa from the Cape Ball sites are indicative of coastal environments. The large, distinctive pollen of thrift (*Armeria maritima*, Fig. 8O) is found in four CB-2 samples (Fig. 7) at site 16. This plant is typically coastal in distribution, as its name suggests, but is also found circumboreally on rocky or gravelly soils in cold arctic regions. *Angelica genuflexa* type (Fig. 8P) of Hebda (1985) is presently common in lowland coastal meadows. The very rare *Abronia* pollen type (Fig. 8Q) indicates the presence of coastal dunes during MIS 4; yellow sand verbena (*A. latifolia*) exists today at a single dune locality on Graham Island.

In summary, the paleoenvironment indicated by the pollen data are treeless coastal tundra, dominated by grasses and sedges and heath plants including *Empetrum*, with a diverse herbaceous flora of arctic-alpine affinity. Most of the rare herbs are entomophilous, and their appearance and abundance in the pollen samples is therefore highly variable. Local conditions include a mosaic of very wet sites with some well-drained areas. The flora mostly suggest a short and cold growing season, probably in a periglacial environment.

Spore and aquatic record

Figure 9A illustrates a *Botryococcus* algal colony recovered from sample CB-2, in association with a fibrous peat layer previously dated at >51 ka BP (Fig. 7). Rare pondweed (*Potamogeton* type) pollen was recovered from the same sample, indicating standing water, probably in a shallow marshy area dominated by sedges and grasses. Spores of cryptogams (ferns and fern allies) reach their highest frequency at the base of this peat layer, and include boreal and tundra taxa such as *Huperzia*, *Botrychium*, and *Selaginella selaginoides* (Figs. 9B, 9C, and 9D, respectively).

An unexpected find in two CB-2 samples is very high frequencies of coprophilous fungal spores, some with fruitification remains (Figs. 9E and 9F). Spores of *Sporormiella* type (Figs. 9E and 9G) are particularly significant, because they are indicators of the dung of mammals, particularly large herbivores such as mammoth, bison, and modern cattle (Davis and Shafer 2006; van Geel et al. 2007; Gill et al. 2013). *Sporormiella* spores collected in traps of bison enclosures have been shown to be local indicators of grazing if frequencies exceed 2.8% of the pollen sum (Gill et al. 2013). Two spectra in sample CB-2 record very high frequencies (69%–91%) of *Sporormiella*, indicating local grazing pressure. The same two spectra also have high values (14%–47%) of *Sordaria* type spores (Figs. 9F and 9H), another coprophilous genus that commonly accompanies *Sporormiella* (van Geel et al. 2007). *Amium* type (Fig. 9I), although rare, is another coprophilous genus. The presence of both fruitifications and dispersed spores of coprophilous fungi confirms that grazers were present at Cape Ball during MIS 4.

Our findings suggest the presence of a local “watering hole” at Cape Ball, where large grazers congregated and defecated during MIS 4. Further research is warranted to elucidate the former presence of mammals on Haida Gwaii and their environment.

Implications for glacial refugia

The early focus of the Haida Gwaii refugium debate centered on whether or not the islands and adjacent continental shelf were completely covered by ice during the Fraser Glaciation, or whether subaerial unglaciated areas were available and served as biological refugia at the LGM. Although no single continuously unglaciated area spanning the LGM has been documented on Haida Gwaii, the weight of evidence favours the existence of some small biological refugia on nunataks, headlands, and interfjord ridges, as well as a potentially large area now submerged in western Hecate Strait (Clague et al. 1982; Mathewes 1989a; Heusser 1989; Byun et al. 1999; Barrie et al. 2005). In addition, eight such areas have been identified on the Alexander Archipelago north of Haida Gwaii (Heusser 1960, 1989; Heaton et al. 1996; Carrara et al. 2007), and may have served as centres of postglacial dispersal of flora and fauna. Evidence supporting a thin ice cover on Haida Gwaii includes very early deglaciation (ca. 15 000 ^{14}C yr BP; Clague et al. 1982; Warner et al. 1982) at Cape Ball on eastern Graham Island, followed by rapid deglaciation of the adjacent continental shelf (Barrie et al. 2005). It is thus likely that several north coast refugia were available to host plant and animal species at the LGM, although probably at different times.

The most recent developments regarding northeastern Pacific coastal refugia come from phylogeography (Shafer et al. 2010), specifically comparisons of DNA variations in populations of living plants and animals from geographically distinct regions. Divergence times for DNA variants can be estimated from known mutation rates, and these can be compared to geological data. This line of enquiry was reviewed by Shafer et al. (2010), who concluded that there is strong evidence for cryptic (hidden) refugia on both the Alexander Archipelago and Haida Gwaii. Cryptic refugia are viewed as unglaciated areas that have not yet been confirmed by geological evidence. When combined with evidence that a genetically unique, north coastal population of lodgepole pine (*Pinus contorta* ssp. *contorta*) is restricted to the Haida Gwaii–Alaska panhandle region (Godbout et al. 2008), the case for signif-

icant refugia continues to strengthen. Lodgepole pine is the first tree to colonize deglaciated soils at all published postglacial sites in this region, and Haida Gwaii is a likely early source for postglacial dispersal of this tree. Other refugial possibilities for trees are southeast Alaska, where subalpine fir (*Abies lasiocarpa*) persists as four, small, probably relictual populations (Heusser 1989); the genus, however, is absent today on Haida Gwaii.

An unexpected recent development is the implication, based on mitochondrial DNA, that the Haida Gwaii area may have hosted a forested (emphasis ours), late Pleistocene glacial refugium. Pruett et al. (2013) documented the mitochondrial DNA phylogeography of six forest-dwelling bird species that would be incompatible with treeless tundra. Estimated divergence ages are in the range of 20 000–30 000 years for four species (Saw-whet owl, Steller’s Jay, Pacific Wren, and Song Sparrow), and are greatest for the Hairy Woodpecker (>70 000 years) and Pine Grosbeak (>120 000 years). If confirmed, these populations evolved during or after MIS 5, and have survived in the Haida Gwaii area since that time.

Survival of tree species and forest birds is clearly a more controversial hypothesis than survival of mosses, lichens, and small vascular plants that exist today on nunataks in presently glaciated areas of coastal Alaska (Heusser 1989). These findings suggest the potential presence of refugia near former lower shorelines where climatic conditions would have been less severe than on mountaintops, supporting the former existence of lowland coastal refugia with trees, an idea first hypothesized by Heusser (1989). The existence of large sea level refugia with some tree cover also supports the contention of Heaton et al. (1996) that brown bears, and perhaps other large mammals, have continuously inhabited the Alexander Archipelago for at least 40 000 years. The presence of late-glacial forest ecosystems on the now-submerged continental shelf of Hecate Strait (Lacourte et al. 2003) supports the possible existence of similar LGM offshore refugia. Based on genetic evidence, it is clear that some of the endemic flora and fauna of the Haida Gwaii region are paleoendemics of pre-LGM origin. Others, however, are likely neoendemics, products of rapid island evolution during postglacial time (Reimchen and Byun 2005).

Our confirmation of glaciation at Cape Ball during MIS 4 contributes to this debate. Determining the age and extent of pre-LGM glaciations is important for understanding the unique biological history of Haida Gwaii, previously discussed in edited summaries (Scudder and Gessler 1989; Fedje and Mathewes 2005) and recent papers. Our findings place constraints on the time available for evolutionary divergence of some endemic populations of flora and fauna. Conditions at Cape Ball during MIS 4 were clearly glacial, raising questions about the survival of many plants and animals at that time. The northern Coast Mountains, and likely other high mountain areas, were covered by an ice sheet (Ward et al. 2007). Paleoecological studies of fossil ground squirrels, plants, and insects in the Klondike region of central Yukon Territory also indicate cold conditions during MIS 4, possibly even more severe than during MIS 2 (Zazula et al. 2011). Palynological evidence of treeless tundra conditions, with an abundance of arctic-alpine flora, indicates a cold climate and a short growing season at Cape Ball around 57 ka ago. Some local flora and fauna were probably extirpated during MIS 4, but many taxa survived or reimmigrated from regional refugia during the MIS 3 interstadial. For example, pollen of the former endemic *Ligusticum calderi* and some non-endemic arctic-alpine plants at Cape Ball indicate that these plants either survived or recolonized from nearby refugia during MIS 3.

Our findings raise the possibility that the Haida Gwaii area supported refugia at the peak of MIS 4 glaciation, and that perhaps many genetically divergent vascular plants, mammals, and birds only evolved after that time. This scenario is supported by the recent phylogeographic data on forest birds. Pruett et al. (2013) estimated divergence ages for four forest bird genotypes at ~20 000 to 30 000 years. These numbers are consistent with the

post-MIS 4 (ca. 46 000–27 500 ^{14}C yr BP) environment at the Cinola Pilot Mill site (Fig. 1), where a forest dominated by spruce (*Picea*) and mountain hemlock (*Tsuga mertensiana*) prevailed under a climate 1–2 °C cooler than present (Warner et al. 1984; Mathewes 1989b).

Our findings from Cape Ball, however, cannot be extended to all of Haida Gwaii without further study. Other sites with similar stratigraphy, such as the sea cliffs at Mary Point (Fig. 1), need to be investigated using optical dating and paleoecological techniques to refine our understanding of paleoenvironments on Haida Gwaii during Early Wisconsinan and older glaciations to better understand the refugial history and evolution of the islands' unique flora and fauna.

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