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Key Points:
- New exposure dating chronology presented for the central coast of British Columbia
- Western margin of the former Cordilleran Ice Sheet was retreating by 18.1 ka
- Numerous ice-free areas existed along the coastline earlier than previously thought

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2

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Retreat of the Western Cordilleran Ice Sheet Margin During the Last Deglaciation

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Abstract The timing of Cordilleran Ice Sheet deglaciation along the central coast of British Columbia, Canada, informs climate forcing and early human migration. Thirty-two ^{10}Be exposure ages from glacial erratics and local bedrock on the western margin of the former ice sheet represent the earliest exposure ages for the Cordilleran Ice Sheet during the last deglaciation. These data show the western ice margin was retreating by 18.1 ± 0.2 ka, consistent with the global record of ice mass loss. In contrast, parts of the southern margin reached a maximum at *ca*. 17.6–16.6 ka, and our data demonstrate a diachronous response of the Cordilleran Ice Sheet during deglaciation. We also show that a low altitude site was exposed by at least 17.7 ± 0.3 ka, implying that numerous ice-free areas existed along the coastal margin by this time, providing a viable route for the first humans entering the Americas.

Plain Language Summary Large ice sheets have advanced and retreated multiple times over the last several hundred thousand years in response to cyclical changes in incoming solar radiation. The Cordilleran Ice Sheet, which once covered much of western Canada, was thought to have advanced and retreated later than others during its last major cycle. The retreat of this ice sheet also opened routes that allowed the first people to enter the Americas. We show that the western margin of the ice sheet retreated earlier than previously thought. Other margins of the ice sheet advanced later, creating a complex picture through time. The early retreat of the western ice margin exposed numerous islands that could have been used by early people migrating southward.

1. Introduction

Records of deglaciation can be used to assess the response of ice sheets to former climate change, track changes in ice extent over time, and constrain ice sheet models (Seguinot et al., 2014, 2016). Despite recent advances (Balbas et al., 2017; Clague, 2017; Lesnek et al., 2018; Margold et al., 2014; Menounos et al., 2017; Stroeven et al., 2010, 2014), the chronology of Cordilleran Ice Sheet retreat remains uncertain. The southern margin of the ice sheet reached its maximum several thousand years after the peak in global ice volume at around 20–19 ka (Carlson & Clark, 2012; Clark et al., 2009; Lambeck et al., 2014; Lisiecki & Raymo, 2005). The reason for a delayed maximum remains unclear.

Closely limiting radiocarbon ages for the Puget Lobe on the southern margin of the ice sheet (Figure 1) show that ice reached its maximum extent between 17.6 and 16.6 ka (Clague et al., 1980; Porter & Swanson, 1998), and surface exposure dating of moraines along the southern margin of the Cordilleran Ice Sheet shows that ice was retreating by *ca*. 16–15 ka (Balbas et al., 2017). Maximum and minimum limiting radiocarbon ages from Vancouver Island (Al-Suwaidi et al., 2006) demonstrate that ice advanced over the island after 19.6 ka and retreated before 15.7 ka. Numerical ice sheet modeling simulates the western margin of the Cordilleran Ice Sheet at the continental shelf at 16 ka (Seguinot et al., 2014, 2016), broadly consistent with previous conceptual models for the region (Fulton, 1991; Mann & Peteet, 1994; Margold et al., 2014; Ryder et al., 1991). If this late maximum was representative of the entire Cordilleran Ice Sheet, it may imply that deglaciation was primarily driven by differences in ice dynamics or regional climate.

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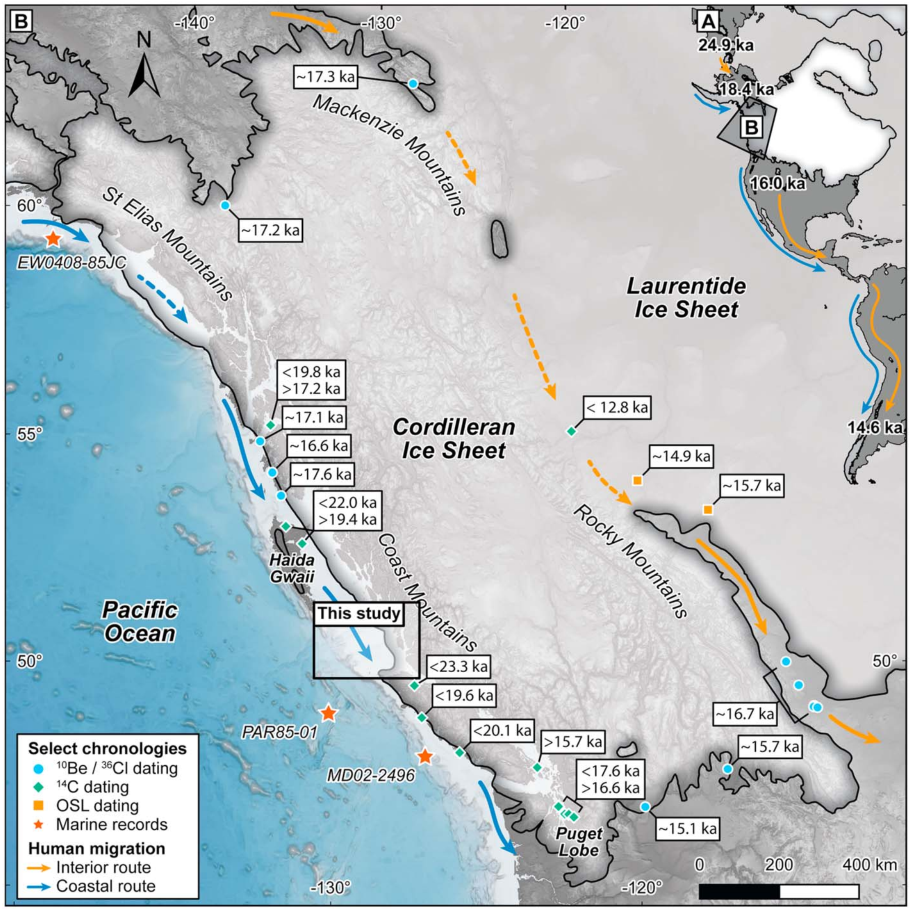

Figure 1. Location of the study area. (a) Two hypothesized routes for human migration into the Americas, with approximate ages at which people are thought to have migrated south (Llamas et al., 2016). (b) Key locations and the approximate extent of the Cordilleran Ice Sheet at around 16 ka (Dyke, 2004). The ice margin north of Vancouver Island is thought to have reached the continental shelf margin at its maximum extent, but its westernmost position off the central coast remains uncertain (this study, the extent of Figure 2). The locations of marine sediment cores discussed in the main text and Figure 4 are shown by red stars and selected chronological information is shown (cf. B. A. Potter et al., 2017; Lesnek et al., 2018; all data are summaries and have not been recalibrated in this figure).

In contrast, minimum limiting radiocarbon ages from Haida Gwaii on the central west coast (Figure 1) have been interpreted to indicate that ice decay was underway by 19.4 ka (Blaise et al., 1990; Clague et al., 1982; Mathewes & Clague, 2017; Warner et al., 1982). Surface exposure ages from islands to the north of Haida Gwaii demonstrate that ice retreat occurred by *ca*. 17.0 ka (Lesnek et al., 2018), similar to deglacial ages from lakes on the Alaskan Peninsula (Misarti et al., 2012). Marine records indicate that ice reached the edge of the continental shelf at its last maximum and formed an extensive margin across Queen Charlotte Sound (Barrie & Conway, 1999, 2002a; Blaise et al., 1990; Davies et al., 2011; Luternauer, Clague, et al., 1989; Luternauer, Conway, et al., 1989). However, the time at which the ice margin left the continental shelf along the central coast of British Columbia (Figure 1) remains uncertain. This region represents a key location in the proposed coastal route for the first human migration into the Americas (Mann & Peteet, 1994; B. A. Potter et al., 2017, 2018). A 200–300-km calving ice margin would have been a significant obstacle for the first humans to navigate by water (Al-Suwaidi et al., 2006; Dixon, 2013; Goebel et al., 2008; Mann & Peteet, 1994). Establishing the timing of deglaciation along the western margin of the Cordilleran Ice Sheet can help to determine the forcing mechanism behind ice retreat, and whether parts of the coastline were ice-free when humans were migrating southward.

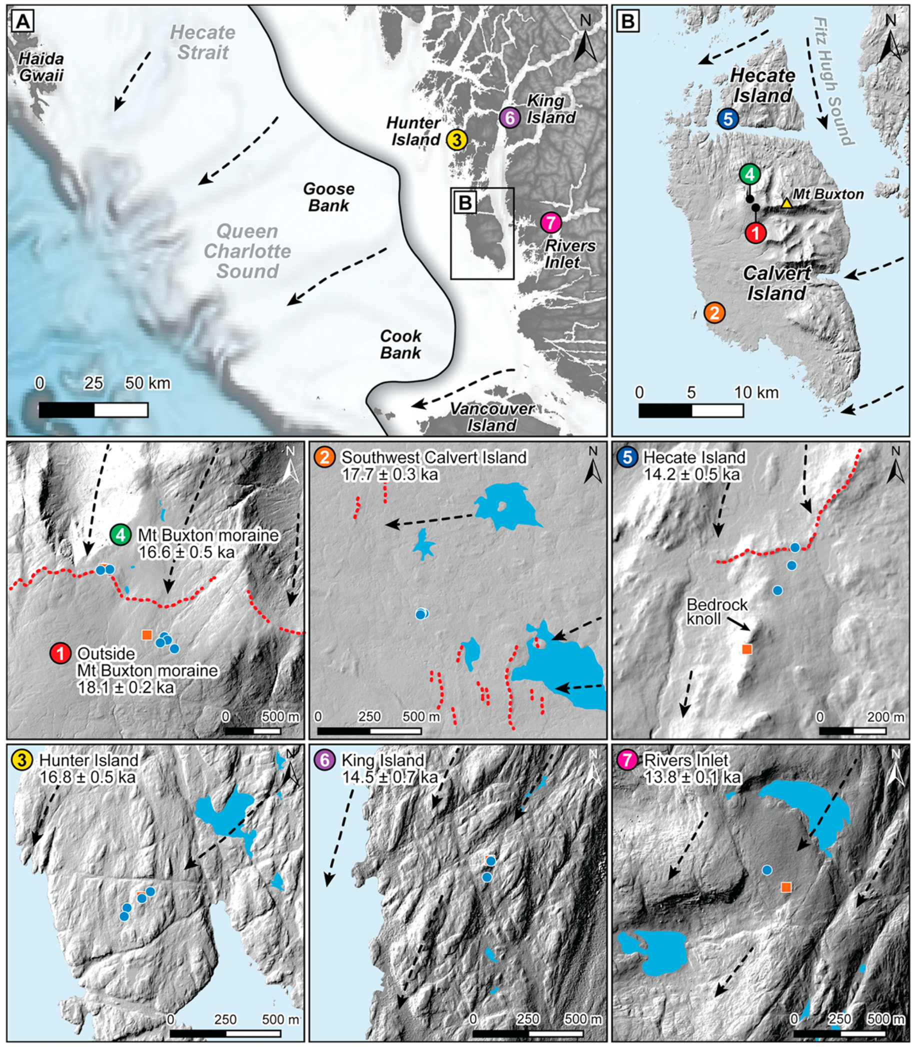

Figure 2. The locations of sites sampled for ^{10}Be exposure dating in this study. Inferred ice flow is shown by black-dashed arrows, moraines by red- dashed lines, boulder samples by blue circles, and bedrock samples by red squares. (a) An overview of Queen Charlotte Sound between Haida Gwaii and Vancouver Island. Goose Bank and Cook Bank paleo-islands are highlighted in relation to our study area. The Cordilleran Ice Sheet reached the continental shelf margin at its last maximum; its hypothesized position at 16 ka is shown by the black solid line, as in Figure 1 (Dyke, 2004). (b) Calvert Island and Hecate Island, with Mt. Buxton highlighted as the highest peak. Ice flowed southward down Fitz Hugh Sound and westward from Rivers Inlet. (1–7) show individual sampling sites on LiDAR imagery labeled according to study sites and median ages shown in Figure 3. A bedrock knoll is highlighted on Hecate Island that likely shielded bedrock samples from sufficient erosion to reset the cosmogenic nuclide concentration in those samples.

2. Study Area

Our study area is situated around Calvert Island on the western coast of British Columbia, Canada, to the east of Queen Charlotte Sound, which fills the continental shelf between Vancouver Island 60 km to the south and Haida Gwaii 200 km to the northwest (Figure 2). The coastline consists of low-relief islands, dissected by channels and sounds. Topography decreases westward from the Coast Mountain Range, although peaks still reach more than 500 m above present sea-level on many islands (e.g., Mt. Buxton, 1017 m above sea level [asl], on Calvert Island; Figure 2). Bedrock in the area is composed of diorite, quartz diorite, granite, granodiorite, and tonalite (Roddick, 1996); Quaternary glacial landform and sedimentary deposits are relatively uncommon. Moraines are generally aligned east-west or northeast-southwest (Figure 2) and in places westward, tracking the receding margin of the Cordilleran Ice Sheet (Eamer et al., 2017, 2018; Neudorf et al., 2015).

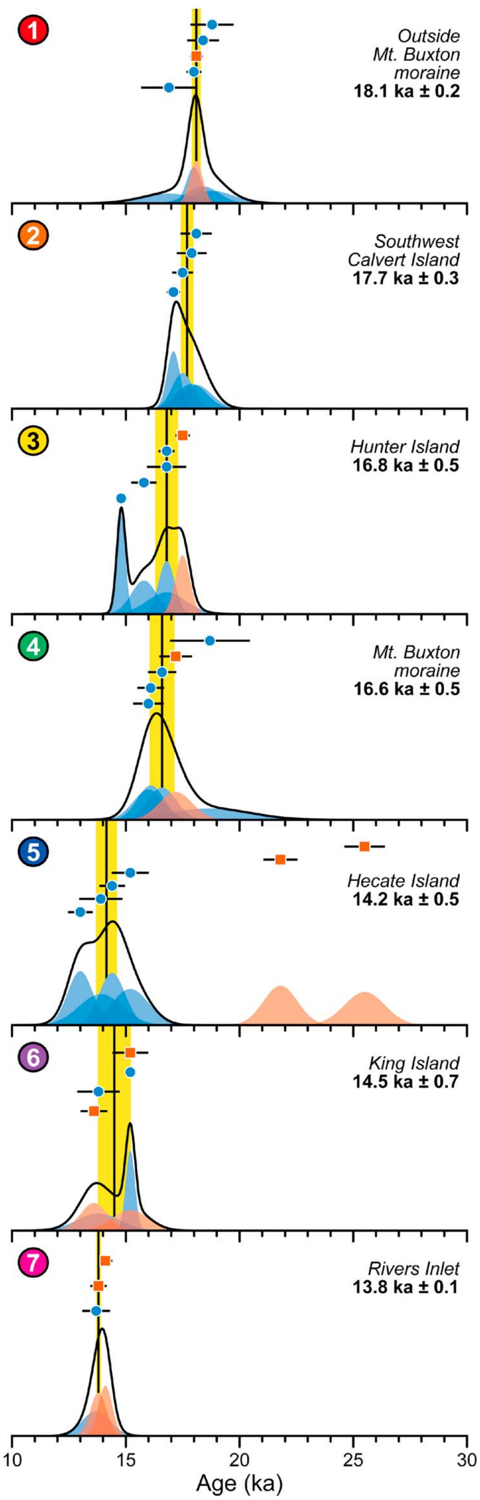

Figure 3. Individual exposure ages and analytical errors from our study sites (1–7; locations shown in Figure 2). The ages are colored according to boulders (blue circles, blue probability plots) and bedrock (red squares, red probability plots). Vertical lines and shading refer to median and interquartile ranges for each study site, noted in the site descriptions. Cumulative density function plots are given for the combined sample exposure ages at each site (thick black curves). Note that the two bedrock ages from Hecate Island have been excluded (see main text for discussion).

At its maximum extent, the Cordilleran Ice Sheet flowed from the Coast Mountain Range westward across the present coastal islands and toward the continental shelf margin (Barrie & Conway, 1999; Luternauer, Clague, et al., 1989; Luternauer, Conway, et al., 1989). The flow direction of the ice sheet generally followed modern channels (e.g., east along Rivers Inlet and southeast along Fitz Hugh Sound; Figure 2; Clague, 1989; Fulton, 1991; Mann & Peteet, 1994; Margold et al., 2014; Ryder et al., 1991). As ice retreated and thinned, it deposited abundant erratics across the landscape (supporting information Figures S1–S7).

3. Methods

To constrain the timing of ice sheet decay along the central coast of British Columbia, we sampled 32 boulders and bedrock surfaces for cosmogenic ^{10}Be exposure dating from seven locations on the western Canadian coast. Samples originate from moraine (n = 8) and erratic (n = 15) boulders and glacially smoothed bedrock (n = 9) deposited and exposed by retreating ice (Figures 2 and 3). All samples were taken from above the established marine limit and were not corrected for glacio-isostatic adjustment as available sea-level data suggests minimal rebound on this part of the coastline (Fedje et al., 2018; Hetherington et al., 2004; McLaren et al., 2014; Shugar et al., 2014). Tandem collection of boulders and bedrock allowed us to assess resetting of nuclide concentrations by subglacial erosion.

We collected samples from topmost rock surfaces using an angle grinder with diamond blade and/or hammer and chisel. Locations and altitudes were recorded using a handheld GPS (supporting information Table S1), and we measured strike/dip and topographic shielding using a compass-clinometer to assess shielding of cosmic rays. Physical and chemical preparation of samples was conducted at the Tulane University Cosmogenic Nuclide Laboratory, and ^{10}Be/^{9}Be isotope ratios were measured at the Purdue University Rare Isotope Laboratory (PRIME Lab). All ^{10}Be ages have been calculated using the CRONUScalc online program (Marrero et al., 2016) with the recent combined production rate of 3.92 atoms g^{-1} a^{-1} and "Sf" scaling scheme (Borchers et al., 2016; Lifton et al., 2014). We did not correct any ages for surface erosion, snow cover, or glacio-isostatic adjustment, so they represent minimum exposure ages. We present the exposure ages with internal analytical errors and as groups from each site using the median and interquartile ranges (Figure 3). Interquartile ranges provide a conservative estimate of age uncertainty in light of possible postdepositional snow cover, erosion, or exhumation (Menounos et al., 2017). Using the median and interquartile ranges yields similar results to the weighted mean and standard error calculated to include uncertainty on the production rate (supporting information Table S1).

4. Results

Erratic boulders exposed by receding ice on Calvert Island yield a median ^{10}Be exposure age (±interquartile range) of 18.1 ± 0.2 ka (n = 5; Figure 3.1) and 17.7 ± 0.3 ka (n = 4; Figure 3.2). Samples from a prominent end moraine deposited on the western flank of Mount Buxton on Calvert Island were exposed at 16.6 ± 0.5 ka (n = 5; Figure 3.4), and erratic boulders from nearby Hunter Island (Figure 2.3) returned an exposure age of 16.8 ± 0.5 ka (n = 5; Figure 3.3). Samples from Hecate Island are younger

(14.2 ± 0.5 ka, $n = 4$; Figure 3.5). The Hecate Island ages are similar to samples exposed by thinning ice at 14.5 ± 0.7 ka ($n = 4$) and 13.8 ± 0.1 ka ($n = 3$) from King Island and Rivers Inlet, respectively (Figures 3.6 and 3.7).

There is high internal consistency within the data set, with low interquartile ranges for each site and median ages between sites that are consistent with ice retreating and thinning north and eastward. However, we exclude two ages obtained from glacially smoothed bedrock samples on Hecate Island since they fall well outside the upper bounds of the interquartile range and do not overlap, within 1σ analytical errors, with any other samples from Hecate Island. The removal of these two bedrock samples results in a small change in the median age (from 14.8 to 14.2 ka) but a large change in the interquartile range (from ±3.1 to ±0.5 ka). Overall, the consistency between ages from moraine boulders, erratic boulders, and glacially smoothed bedrock suggests that they closely record the time of ice retreat. We propose that the two outliers likely result from nuclide inheritance due to insufficient erosion by ice, and we suggest that a bedrock knoll on Hecate Island helped to protect the two bedrock samples from erosion (Figure 2.5).

5. Discussion

5.1. Diachronous Marginal Retreat

Our ^{10}Be dating chronology reveals that the western margin of the Cordilleran Ice Sheet along the central coast of British Columbia retreated to the present-day coastline by at least 18.1 ± 0.2 ka; earlier than simulated by ice sheet models (Seguinot et al., 2016). The fact that we present minimum exposure ages strengthens our conclusion that deglaciation occurred earlier along this part of the coastline than previously thought (Dyke, 2004). If the Cordilleran Ice Sheet extended to the continental shelf on the central coast during the Last Glacial Maximum, it did so before 18.1 ka.

The timing of deglaciation reported here agrees with findings from north of the study area (Blaise et al., 1990; Clague et al., 1982; Mathewes & Clague, 2017; Warner et al., 1982), implying that the western edge of the Cordilleran Ice Sheet advanced across Hecate Strait at *ca*. 30.0 ka and reached Haida Gwaii after *ca*. 22.0 ka, but was retreating by *ca*. 19.4 ka (Figure 4i). Conversely, maximum and minimum limiting radiocarbon-dated bones from Shuká Káa on Prince of Wales Island, to the north of Haida Gwaii, suggest ice advanced over the cave between *ca*. 19.8 and 17.2 ka (Lesnek et al., 2018; Figure 4g). Exposure ages from the same area suggest marginal retreat at 17.0 ka (Lesnek et al., 2018; Figure 4h), and lake records are consistent with deglaciation in the Gulf of Alaska by around 17.0 ka (Misarti et al., 2012). Maximum and minimum limiting radiocarbon ages from Vancouver Island between *ca*. 19.6 and *ca*. 15.7 ka do not provide sufficient constraint to assess whether ice was retreating by 18.1 ka south of Calvert Island (Figure 4l). Tightly limiting radiocarbon ages from the Puget Lobe on the southern margin of the ice sheet suggest that this part of the Cordilleran Ice Sheet reached its maximum extent after *ca*. 17.6 ka but before *ca*. 16.6 ka (Porter & Swanson, 1998; Figure 4l).

The western ice margin was the only marine terminating section of the Cordilleran Ice Sheet, so retreat may have been triggered by increased calving induced by eustatic sea-level rise (Figure 4a) and rapid deglacial isostatic adjustment (Clague, 1985, 1989; Margold et al., 2013). Calving of marine-terminating sections of the ice margin likely accounts for large increases in ice-rafted debris at 17.7–18.5 ka in marine core PAR85-01 off Queen Charlotte Sound (Blaise et al., 1990). Independent of the specific means by which ice was lost from the western margin prior to 18.1 ka, the response was coeval with global deglaciation and rising Northern Hemisphere summer insolation after *ca*. 19 ka (Figure 4b). Our exposure data and previous work collectively show a diachronous retreat pattern of the Cordilleran Ice Sheet's western (Figures 4g–4j) and southern margins (Figures 4l and 4m).

Following initial, early deglaciation on the western coast, we suggest that the advance (or still-stand) of ice at *ca*. 17.6–16.6 ka represents a consistent response of the whole ice sheet to a regional climatic event at a time when other ice sheets were receding (Figure 4). On Calvert Island, a moraine deposited at 16.6 ± 0.5 ka on the western flank of Mt. Buxton accords with the well-dated maximum of the Puget Lobe *ca*. 17.6–16.6 ka (Porter & Swanson, 1998) and exposure ages from the northern, western, and southern margins of the ice sheet. These data imply an advance or still-stand of the ice sheet in several locations at this time (Balbas et al., 2017; Stroeven et al., 2010, 2014; Figures 4f–4m). Marine sediments west of Vancouver Island also record an increase in ice-rafted debris consistent with the rapid advance then

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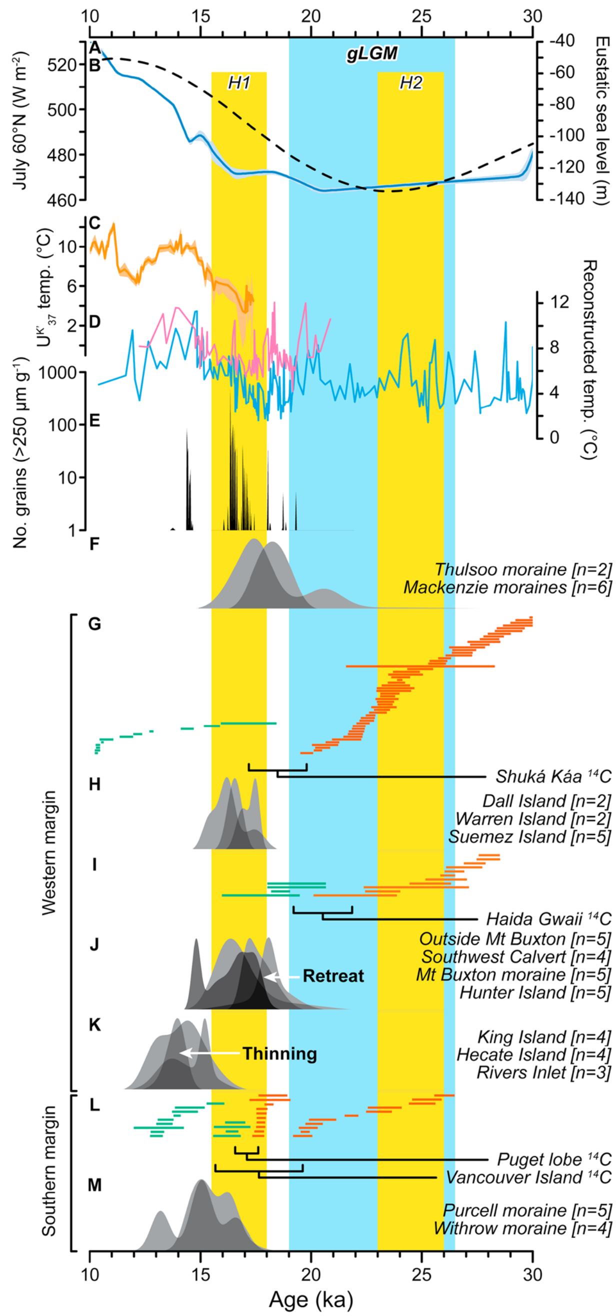

Figure 4. A synthesis of ice margin chronologies and selected proxy records relating to the timing of Cordilleran Ice Sheet deglaciation. The global Last Glacial Maximum (Clark et al., 2009; gLGM) and Heinrich events 1 and 2 (H1 and H2) are shown for reference. (a) Northern Hemisphere insolation at 60°N in July (Berger & Loutre, 1991). (b) Ice volume equivalent sea level as a reference for global ice volume (Lambeck et al., 2014). (c) Alkenone paleotemperature reconstructed from marine core EW0408-85JC in the Gulf of Alaska (Davies et al., 2011; Praetorius et al., 2015). (d) Reconstructed Mg/Ca temperatures for *N. pachyderma* (blue line) and *G. bulloides* (pink line) from marine core MD02-2496 (Taylor et al., 2014). (e) Ice-rafted debris record on a logarithmic scale from core MD02-2496 (Cosma et al., 2008). (f–m) Recalibrated ^{10}Be exposure ages from (f) the northern ice sheet margin (Stroeven et al., 2010, 2014), (h) the western ice sheet margin, north of Haida Gwaii (Lesnek et al., 2018), (j) and (k) this study, (m) moraines on the southern ice sheet margin (Balbas et al., 2017). For consistency, all exposure ages in this figure have been recalibrated using the CRONUScalc online program (Marrero et al., 2016) with the combined production rate of 3.92 atoms g^{-1} a^{-1} and "Sf" scaling scheme (Borchers et al., 2016; Lifton et al., 2014) and are shown as normalized cumulative density function plots. (g–l) Minimum (green, younger) and maximum (red, older) radiocarbon ages from (g) Shuká Káa on Prince of Wales Island (Lesnek et al., 2018), (i) Haida Gwaii (Blaise et al., 1990; Warner et al., 1982), (l) the Puget lobe (Anundsen et al., 1994; Leopold et al., 1982; Mullineaux et al., 1965; S. C. Porter & Swanson, 1998), and (l) Vancouver Island (Alley, 1979; Blais-Stevens & Clague, 2001; Clague et al., 1980; Dyck & Fyles, 1962, 1963; Dyck et al., 1965, 1966; Keddie, 1979; Lowdon & Blake, 1978; Walton et al., 1961; Ward et al., 2003). Gray horizontal brackets respectively denote the youngest maxima and oldest minima of ice advance and retreat. (i and l) Recalibrated using intCal13 (Hetherington et al., 2003; McNeely et al., 2006; Reimer et al., 2013; Southon et al., 1990; Stuiver et al., 2017); see supporting information Table S2 for recalibrated radiocarbon ages and associated references.

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retreat of the Puget and Juan de Fuca ice lobes (Cosma & Hendy, 2008; Hendy & Cosma, 2008; Taylor et al., 2014; Figure 4e).

Short-lived cooling of surface ocean temperatures in the eastern Pacific (Figure 4d) and Gulf of Alaska (Figure 4c) at 17–16 ka may have slowed the retreat of ice on the western margin and triggered the advance of the Puget Lobe to the south (Cosma & Hendy, 2008; Davies et al., 2011; Hendy & Cosma, 2008; Maier et al., 2018; Praetorius & Mix, 2014; Praetorius et al., 2015; Taylor et al., 2014). The regional signature of ocean temperatures in the Northeast Pacific during deglaciation has been linked to the strength of the California Current driven by movement of the Intertropical Convergence Zone, in turn linked to the growth and decay of the Laurentide and Cordilleran ice sheets (Taylor et al., 2015). This cold event, concurrent with Heinrich event 1 (Figure 4), may also imply a regional response of the Cordilleran Ice Sheet to hemispheric changes in climate during the last deglaciation (Jones et al., 2018).

Between 16.6 and 14.2 ka, net retreat of the western ice sheet margin was only 10-km northward of Mt. Buxton, but it thinned markedly. Hecate Island was exposed at 14.2 ± 0.5 ka, likely during retreat following a readvance of the ice sheet given the similarity between our exposure ages and radiocarbon ages for a readvance on Calvert Island (Eamer et al., 2017). At a similar time, two other sites were exposed by ice thinning into fjords below: 14.5 ± 0.7 ka for King Island and 13.8 ± 0.1 ka for Rivers Inlet (Figures 2 and 3). Elevation differences in underlying topography suggest a shallower ice surface between samples from King Island (~172 m asl) and Hecate Island (~86 m asl) at *ca*. 14.5–14.2 ka compared to samples from Mt. Buxton (~636 m asl) and southwest Calvert Island (~39 m asl) at *ca*. 18.1–16.6 ka (supporting information Table S1). The shallower ice surface could reflect change from an ice sheet unconstrained by local topography to a series of glaciers fed by the main ice sheet but topographically constrained within valleys and fjords (Clague, 1985). This finding is consistent with a trend of ice sheet thinning by around 14.0 ka, during which the Cordilleran Ice Sheet contributed 2.5–3.0 m to eustatic sea-level rise (Lambeck et al., 2014; Margold et al., 2014; Menounos et al., 2017), potentially contributing to meltwater pulses at this time (Gomez et al., 2015; Gregoire et al., 2016, 2012; Ivanovic et al., 2017).

5.2. Implications for Early Human Migration

Our chronology demonstrates that a coastal route used by the first humans entering the Americas was viable earlier than previously thought, providing important geological constraints for early coastal occupation (McLaren et al., 2018). Genetic data suggest that the first human migration south of the Cordilleran Ice Sheet may have occurred after *ca*. 16.0 ka (Llamas et al., 2016; Moreno-Mayar et al., 2018; Raghavan et al., 2015; Skoglund & Reich, 2016), but the route taken around the continental ice sheets remains unclear (Potter et al., 2017, 2018). One hypothesis suggests people traveled via an interior corridor between the margins of the decaying Laurentide and Cordilleran ice sheets (e.g., Goebel et al., 2008; Mandryk et al., 2001). The chronology and viability of this interior corridor remain contentious, but it likely became ice-free between 15.0 and 13.0 ka, and viable sometime thereafter (Heintzman et al., 2016; Hickin et al., 2015; Jackson et al., 1999; Munyikwa et al., 2017; Pedersen et al., 2016; B. A. Potter et al., 2017). A second hypothesis posits that people traveled south along the west coast of British Columbia (Erlandson et al., 2011; Lesnek et al., 2018; Mandryk et al., 2001). Postglacial sea-level change west of Calvert Island before 16 ka remains uncertain (Shugar et al., 2014) but, by 16–15 ka, wave-cut terraces and intertidal shellfish remains from the now-submerged Goose Bank (Barrie & Conway, 2002b) and Cook Bank (Luternauer, Clague, et al., 1989) imply that a strong local isostatic response exposed paleo-islands (Fedje et al., 2018; Hetherington et al., 2003, 2004; Luternauer, Clague, et al., 1989; McLaren et al., 2014; Shugar et al., 2014).

Our data and those from previous studies show that coastal islands, including Calvert Island, Haida Gwaii, Goose Bank, and Cook Bank (Figure 2), were ice-free by at least 18.1 ka. Islands further north were also ice-free from around 17.0 ka (Lesnek et al., 2018). Fossil evidence for deglacial refugia from these islands, as well as Haida Gwaii (Mathewes et al., 2015) and Vancouver Island (Al-Suwaidi et al., 2006; Ward et al., 2003) add to the story of an early habitable coastal route, likely before an interior route became viable. The pattern of ice retreat was complex, and ice remained proximal until *ca*. 15.0 ka (Davies et al., 2011; Lesnek et al., 2018; Menounos et al., 2017), but ice-free or partially ice-free islands along the coast may have facilitated southward human migration (Erlandson et al., 2011; Mandryk et al., 2001). Our new chronology adds important geological evidence to the debate around a coastal migration route taken by early humans entering the Americas (McLaren et al., 2018).

6. Conclusions

Our study shows that retreat of the western margin of the Cordilleran Ice Sheet during the last deglaciation occurred earlier than previously thought, by at least 18.1 ka and prior to the maxima of other parts of the ice sheet. Our data demonstrate a diachronous marginal response in which the western margin retreated in-phase with global ice volume and Northern Hemisphere insolation. Subsequently, at around 17–16 ka, the ice sheet responded regionally to hemispheric changes in deglacial climate, resulting in an ice advance or stillstand. Our new reconstruction demonstrates that at least parts of the western coastal margin were exposed by 18.1 ka, strengthening the case for a viable coastal route available to the first humans entering the Americas.

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