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Slowstands, stillstands and transgressions: Paleoshorelines and archaeology on Quadra Island, BC, Canada

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ABSTRACT

On Quadra Island, west coast Canada, a series of marine terraces formed during a period of rapid marine regression from 200 m to 1 m above modern levels between ca. 14,500 and 12,000 years ago. Within this period of regional marine regression, evidence points to brief periods of sea level stillstand and even marine transgressions. It is hypothesized that during these anomalous periods, global meltwater events created a local signature on the Quadra Island sea level curve by slowing, halting and/or inversing the regional sea level regression trend. This is revealed through identification of high elevation paleoshorelines, landscape terracing and other stranded marine features from LiDAR Digital Elevation Models (DEMs) and subsurface investigation. These paleomarine terraces are believed to have developed during brief marine stillstands, slowstands and minor marine transgressions. Pauses or slowing periods of regression appear to result from global eustatic rise briefly matching or exceeding local isostatic and tectonic uplift. The ages of these terraces, based on local sea level history and radiocarbon dating of some of the raised marine features, match well to the ages of coral-based marine terraces sequences associated with periods of rapid global sea level rise. A number of early post glacial to earliest Holocene archaeological sites are associated with the Quadra marine terraces. These associations suggest an improved approach to location of early archaeological sites dating to times of rapid sea level change.

1. Introduction

Discovery of archaeological sites older than ca. 13,000 years ago on Canada's west coast is challenged by the dynamic nature of sea level change during early post-glacial time. Here we examine the sea level history of the Quadra Island area (Fig. 1) and link that history to climate drivers, paleoshoreline development and early peopling. This work shows that a closer look at regional sea level histories helps to address some of these challenges.

Through interpretation of LiDAR-based (Light Detection and Ranging) data and geoarchaeological field investigations we identified a series of paleoshoreline features consistent with interruptions in, otherwise rapid, post-glacial marine regression. Some of these features were identified previously (Fedje et al., 2018), while others have become apparent from recent archaeological work and through interpretation of recently obtained LiDAR-based Digital Elevation Models (DEMs). Interruptions in sea level regression have been hypothesized to relate to isostatic and eustatic fluctuations during highly dynamic early post-glacial time (Fedje et al., 2018). Our goal is to identify those paleoshoreline features that would have been highly attractive to early coastal people and, at the same time, relatively enduring on the landscape, within an otherwise rapidly changing coastal environment (make the paleoshoreline 'haystack' small enough to find early post-glacial archaeological 'needles').

The work presented here builds upon recent investigations that have increased the prospect of locating early post-glacial archaeological sites on the Northwest Coast by combining LiDAR-based Relative Sea Level (RSL) landscape models with predictive models (Fedje et al. 2018, 2021; Letham et al., 2018; Lausanne et al., 2019; McLaren et al., 2015; Vogelaar, 2017).

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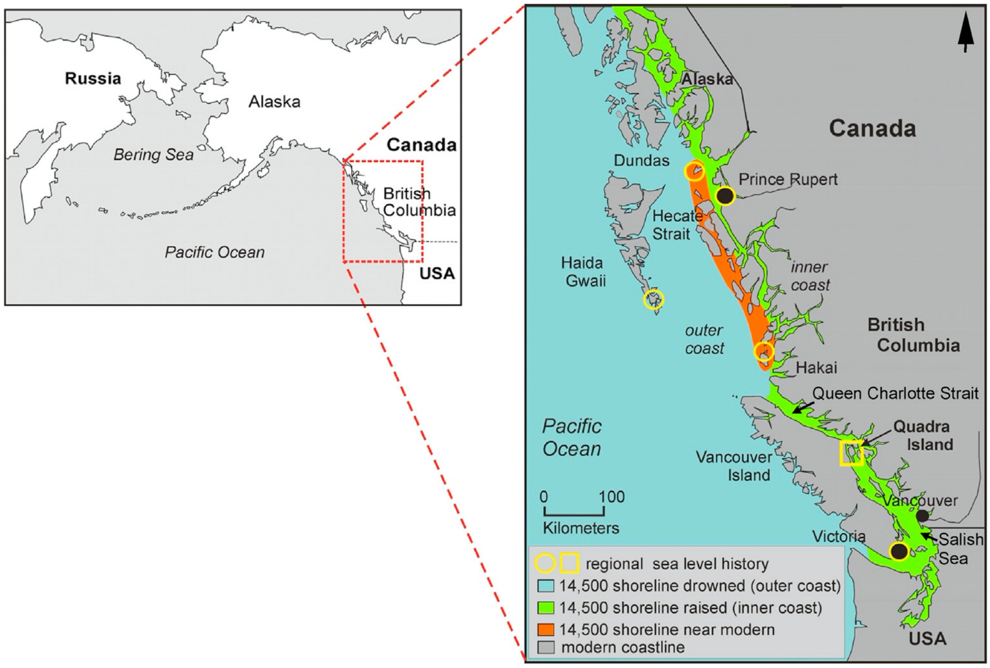

Fig. 1. Location of Quadra Island and present position of 14,500-year-old shorelines. Quadra Island polygon is detailed in Fig. 2.

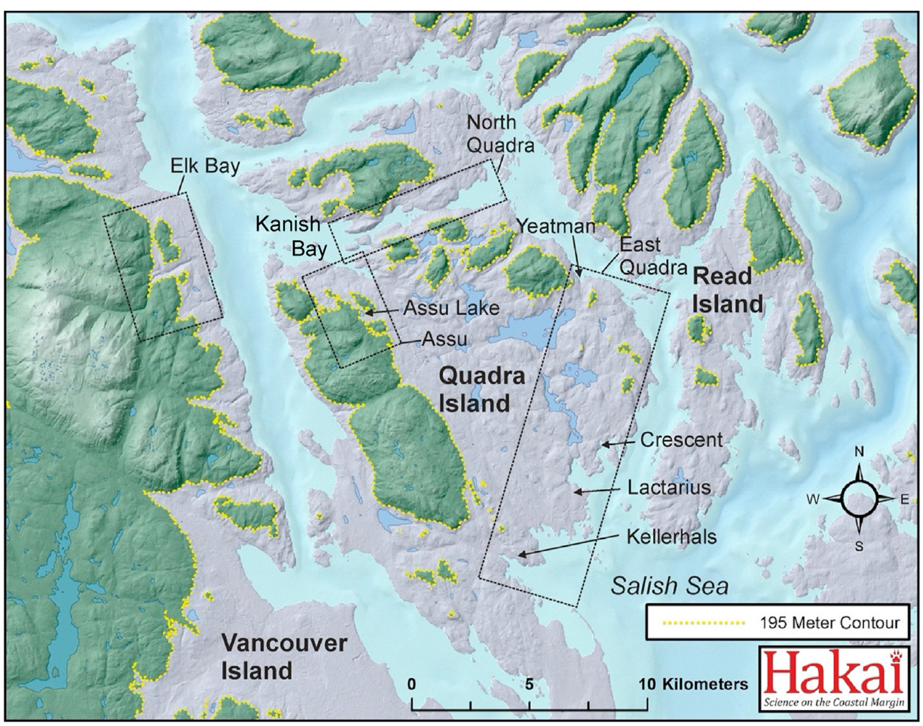

Fig. 2. Quadra Island early post-glacial and present environs: modern shoreline (grey) and ca. 14,300 years ago (green) with aerial LiDAR survey areas of Elk Bay (Vancouver Island), North and East Quadra and Assu (indicated by dashed polygons); and key locations mentioned in text. The Assu and Elk Bay polygons are detailed in Figs. 5 and 6 below. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Ages presented here as 'years ago' are calendar years before 1950 AD as calibrated using the Calib 8.2 radiocarbon calibration programme (Stuiver et al., 2020). Shoreline elevations are in metres above high tide (m), as the focus of these investigations is on locating terrestrial shorelines where human activity might be anticipated. On Quadra Island, high tide ranges from approximately 2.5 to 3 m above mean sea level. All elevations presented here are in reference to above high tide (aht).

2. Glacial history: deglaciation and regional glacial advances

On the Pacific Coast of Canada and Alaska, the late Wisconsin

Glacial Maximum dates to about 19,000 years ago, with retreat of ice on the outer coast beginning shortly thereafter (Clague and James, 2002; Darvill et al., 2018; Menounos et al., 2017; Lesnek et al. 2018, 2020; Shaw et al., 2019). Ice cover on the inner coast, including the environs of Quadra Island and the Salish Sea, was of significantly longer duration. The maximum extent of Fraser Glaciation ice in the Salish Sea – Queen Charlotte Strait area occurred approximately 17,000 to 16,000 years ago (Vashon Stade), after which there was rapid retreat (Clague and James, 2002; Menounos et al., 2009; Mosher and Hewitt, 2004).

By 15,300 years ago the Salish Sea was free of ice and glaciers were restricted to mainland fjords (Menounos et al., 2009). However, there were several glacial advances in the subsequent millennia. In mainland valleys, adjacent to the southern Salish Sea, significant advances occurred ca. 14,500 and 13,500 years ago (early Sumas advances) and during Younger Dryas time (Squamish advance) ca. 12,900 years ago (Armstrong et al., 1965; Clague et al., 1997; Clague and James, 2002; Friele and Clague, 2002; Menounos et al. 2009, 2017). Mood (2015) present evidence suggesting an early Younger Dryas age advance dating from about 12,900 to 12,700 years ago at the Franklin Glacier on Mount Waddington (just above the head of Knight Inlet and visible from Quadra Island) as well as a series of later Holocene advances.

3. Relative sea level

Relative sea level is a regional phenomenon, especially in high latitude areas proximal to large accumulations of ice where substantial isostatic differences may result from the rates and timing of glacial advances and recessions. In many areas, shoreline position shifted rapidly during early post-glacial times. On the Northwest Coast, outer coast shorelines dating to early post-glacial times are located up to 150 m below modern levels, while inner coast shorelines can be found stranded up to 200 m or more above modern sea level (Clague et al., 1982; Fedje et al., 2005; Josenhans et al., 1997; Shugar et al., 2014, Fig. 3).

The Quadra Island area sea level history is largely one of marine regression (James et al., 2005; Fedje et al., 2018). It spans the past 14,500 to 15,000 years. Marine microfossils recovered from Assu Bog and Assu Lake (Figs. 4 and 5) show that ocean levels were at 175 m ca. 14,300 years ago and above 195 m somewhat before that time. Regression was rapid in early post-glacial time (ca. 14,500 to 12,000 years ago) with shoreline position, relative to modern, falling from above 197 m to ca. 1 m above the elevation of the modern tidal limit during this interval. Relative sea level then rose to ca. 3 m between 12,000 and 11,000 years ago and fell gradually to modern thereafter. The elevation and duration of the marine maximum is not known. Based on thorough examination of the LiDAR-derived DEMs, a well-developed but undated terrace at ca. 240 m in the nearby Elk Bay area (Fig. 6) may approximate the marine highstand for this region. On Quadra a series of raised marine terraces observed at elevations of ca. 195 m, 153 m, 75 m, 28 m, 12 m and 3 m above the modern shoreline suggest that the rapid fall in relative sea level position during early post-glacial time was interrupted by stillstands, slowstands and minor marine transgressions. The 195 m, 28 m, 12 m and 3 m terraces were identified through earlier investigations (Fedje et al., 2018; Lausanne, 2018; Lausanne et al., 2019) while other terraces were identified from analysis of recently obtained LiDAR (Figs. 5 and 6). The precise age range for most of these terraces is not known as the existing sea level history is based on relatively few data points. The RSL curve developed for the area (Fig. 4) provides a close approximation of the respective ages. LiDAR-focused research and archaeological predictive modeling focussing on the 28 m and 12 m paleo-terraces were subsequently employed to target archaeological survey (Lausanne, 2018; Lausanne et al., 2019).

3.1. Isostatic component

In the Quadra area rapid marine regression (>200 m to 1–2 m) that took place between ca. 14,500 and 12,000 years ago arose from post-glacial isostatic rebound associated with decay of the Cordilleran Ice Sheet (CIS) outpacing eustatic sea level rise (Fedje et al., 2018; James et al., 2005; Menounos et al. 2009, 2017). Variation in the rate of regression may also be related to periods of abrupt climate change during that time. Although post-14,500 years ago glacial advances are not well constrained for the Quadra area, they may have had some effect on local sea level history as ice advanced down mainland valleys (cf. Friele and Clague, 2002; Menounos et al., 2009), potentially slowing isostatic rebound. This slowdown may have contributed to sea level stillstands or minor transgressive events. It is possible that glacier advances where ice reached tidewater occurred in mainland valleys east of the Quadra environs during the time of the Sumas (14,500–14,000 and 13,500–13,200 years ago) and Younger Dryas (12,800–11,500 years ago) advances documented for mainland valleys in the environs of the southern Salish Sea (Friele and Clague, 2002; Menounos et al., 2009).

3.2. Eustatic component

For Quadra Island, the rate of RSL regression is largely a balance between the rate of global eustatic rise and the rate of isostatic rebound. By the time that Quadra was ice-free (ca. 15,000 to 14,500 years ago) global sea level had risen from ca. −130 m to −100 m relative to modern levels (Lambeck et al. 2014, 2017; Peltier and Fairbanks, 2006). Significant slowing in global eustatic rise appears to have occurred at ca. 15,000 and 12,800 years ago. A ca. 15,000–14,700 years ago (immediate pre- Bølling-Allerød) slowing appears to include a brief reversal in sea level change (Fig. 3; Lambeck et al., 2014, 2017). The slowdown at ca. 12,800 during the Younger Dryas cold interval [12,800–11,500 years ago - Lohne et al., 2014; Mangerud 2021], culminated at 12,000 to 11,600 years ago (Abdul et al., 2016). After ca. 7000 years ago global eustatic rise was much more gradual. Khanna et al. (2017) and Abdul et al. (2016) noted rapid sea level rise that they attributed to global meltwater pulses during the Bølling-Allerød warm period and immediately following the Younger Dryas cold period. These include MWP-1a (Abdul et al., 2016; Blanchon et al., 2021; Fairbanks, 1989) dating to ca. 14,500–14,200 years ago, pulses at ca. 14,150–14,050, 13,800–13,650, 13,550–13,300, 13,150–12,900 and 12,800–12,550 years ago (Khanna et al., 2017) as well as the immediately post-Younger Dryas MWP-1b (Abdul et al., 2016; Blanchon et al., 2021; Mortlock et al., 2016) at ca. 11,400–11,100 years ago. Khanna et al. (2017) correlate most of these meltwater events to warm periods identified in cores from the Greenland Ice Sheet.

Times of rapid meltwater-driven eustatic sea level rise would counteract the effects of isostatic rebound on relative sea level. Meltwater pulses appear to be better constrained than glacial advances and, thus, provide greater prospective for determining associations with observed paleoshoreline features. Both of these processes would have slowed RSL fall and allowed more time for marine processes to develop shoreline features. The longer the duration of sea level stability, the more visible such features can be anticipated, with concomitant increased visibility of any associated archaeological record. In order to remotely identify these potential paleoshoreline features, access was needed to observe the bare-earth inland topography, without the dense rainforest masking the terrain. Aerial LiDAR was flown over large swaths of Quadra Island to obtain this data and digitally model the paleolandscape.

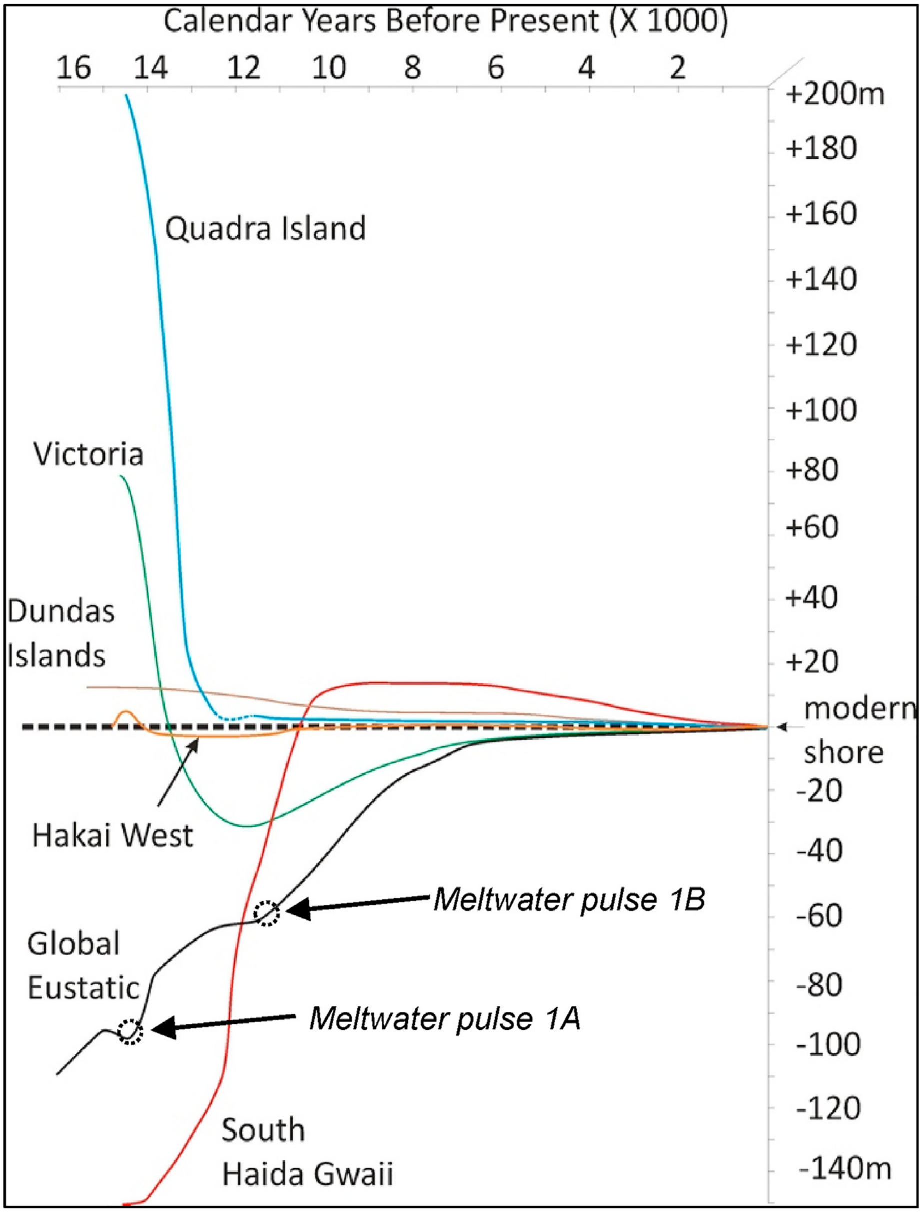

Fig. 3. Regional relative sea level histories: Quadra Island (Fedje et al., 2018; James et al., 2005), Victoria - early post-glacial (James et al., 2009), mid to late Holocene (Fedje et al., 2009); Dundas Islands (McLaren et al., 2011); Hakai (McLaren et al., 2014); global eustatic (Lambeck et al., 2017); meltwater pulses (Abdul et al., 2016); Haida Gwaii (Fedje et al., 2005).

4. Methods and data

To connect sea level history to human use of the paleolandscape, we examined relict, shoreline features and archaeological evidence indicating association with marine processes. These paleoshoreline features were revealed through LiDAR. These data went through a series of post-processing techniques to generate the DEMs. This entailed conversion to point cloud data and stripping of forest canopy returns. The lowest returns were gridded to yield a bare earth grid, followed by hillshade illumination methods to create bare-earth Digital Terrain Models (DTMs). Through this process, paleoshoreline features were able to be identified. These include: paleo-deltas and estuaries; relict beach ridges, berms and terraces; and paleo-tombolos and spits. Archaeological sites were discovered by integrating the modeling data with conventional archaeological survey method.

4.1. Archaeological method

Archaeological investigation focused on survey for archaeological sites in areas selected based upon landscape and predictive modeling (Fedje et al., 2021; Lausanne, 2018; Lausanne et al., 2019; Vogelaar, 2017). Landforms considered to have high archaeological potential were subject to foot survey for surface evidence and shovel testing for buried cultural deposits. Tests were normally 50 cm square and 100 cm deep. These were excavated by shovel and trowel in 5 cm increments with sediment matrix dry screened through 6 mm mesh. One metre square evaluative excavations, to two or more metres depth, were conducted at select sites where test or surface evidence suggested the presence of early archaeological components. These were excavated by natural layer or 5 cm increments with all sediment water-screened through 3 mm mesh.

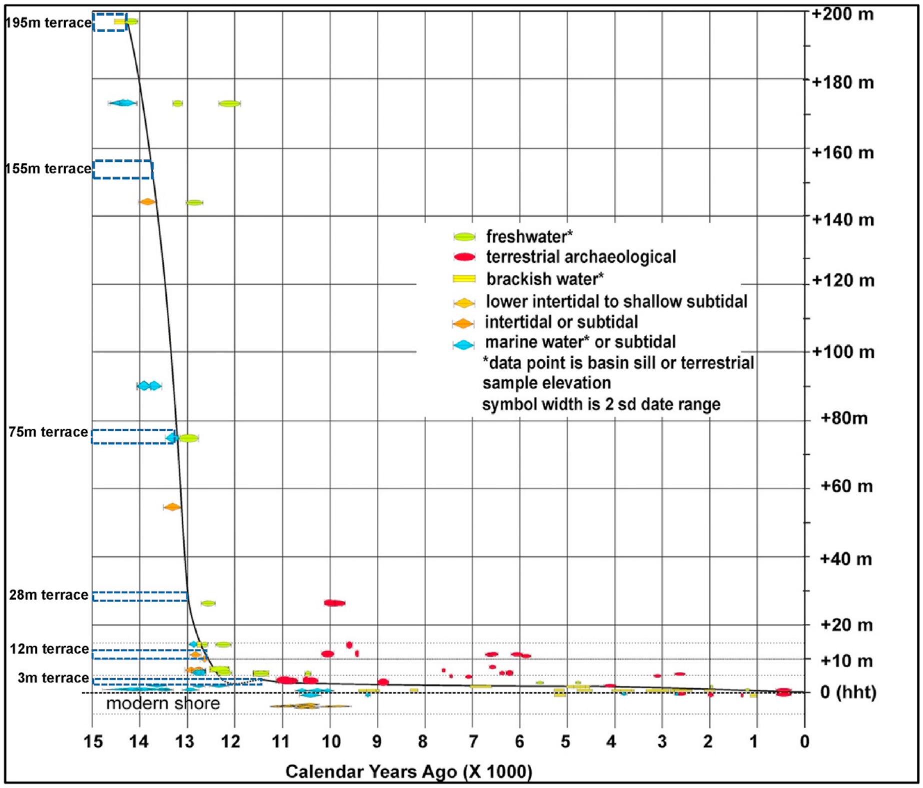

Fig. 4. Sea level curve, Quadra Island from adapted from Fedje et al. (2018). Approximate elevation ranges for terraces observed on LiDAR are shown as dashed rectangles.

4.2. LiDAR

The first set of aerial LiDAR surveys were flown over sections of Quadra Island from a fixed-wing aircraft equipped with a Riegl VQ-580 laser scanner in 2014. One area of interest covered a northern section of the island (labeled "North Quadra" in Fig. 2) and the other area of interest was the southeastern side (labeled "East Quadra" in Fig. 2). The LiDAR dataset was processed into the NAD83(CSRS) geodetic datum (UTM Zone 10) and yielded an average point cloud density of 19 points/m^2.

Post-processing included removal of the vegetation layer and producing a bare-earth DEM. Ellipsoidal heights (of vertical datum) of the ground points were then converted to CGVD28 using the HTv2.0 geoid. The data were gridded to produce a final DEM with a horizontal resolution (or cell size) of 1 m^2 . The DTM was then created by applying a multidirectional hillshade. This process helped to visually enhance the data and allowed for paleocoastal features to be discerned. For further details, see Lausanne et al., (2019).

In 2018, another aerial LiDAR survey (Figs. 2 and 5) was conducted over a section on western Quadra Island to acquire higher elevation data in an attempt to reveal the earliest evidence of sea level stillstands on Quadra Island. These data are consistent with the above parameters (e.g., NAD83 (CSRS) geodetic datum), resulted in a 16 points/m^2 point cloud density, and was also gridded to a 1 m^2 resolution DEM. Additional LiDAR data was acquired from Interfor Corporation in 2018 (labeled "Elk Bay" in Figs. 2 and 6).

4.3. Paleoshoreline features

Shoreline features that might be expected to form during sea level stillstands, slowstands and minor marine transgressions include terraces, beach ridges, berms, spits and tombolos. These features may have developed sufficiently to be visible in LiDAR DEMs if such events were of sufficiently long duration. We conducted an analysis of bare earth DEMs to elucidate types of features that formed during periods of higher sea level and are now visible from DEM imagery at inland and elevated locations (Lausanne, 2018; Lausanne et al., 2019). Exposure classes were used following Howes et al. (1994) shoreline classification for British Columbia. Geomorphic feature types follow Earle (2019), Mangor (2004) and Otvos (2000).

4.4. -Paleo-deltas and estuaries

Paleo-deltas and estuaries tend to be relatively visible as they often show terracing and low-slope areas large enough to see in LiDAR images. Development of relatively steep foreset beds (Fig. 11) or post-regression erosion in front of these low-slope alluvial landforms make them distinct. Examples of these landforms include the Crescent Channel (12 m) and Lactarius Road (28 m) archaeological sites and a 160 m elevation terrace near Elk Bay (Figs. 6, 10 and 12). These features may contain evidence of contemporaneous human activity although most evidence is likely to be found in supratidal areas immediately behind these landforms rather than in these paleo-intertidal areas.

4.5. -Relict beach ridges

Beach ridges are stranded, semi-parallel, multiple ridge formations that are deposited above spring tide elevations by high energy waves (Hesp, 2006; Otvos, 2000). All the ridges identified in the Quadra area have been determined to be non-glacial as they are situated below the elevation of the radiocarbon constrained post-glacial marine limit and are associated with specific contour ranges (Fedje et al., 2018). They tend to be most visible along semi-

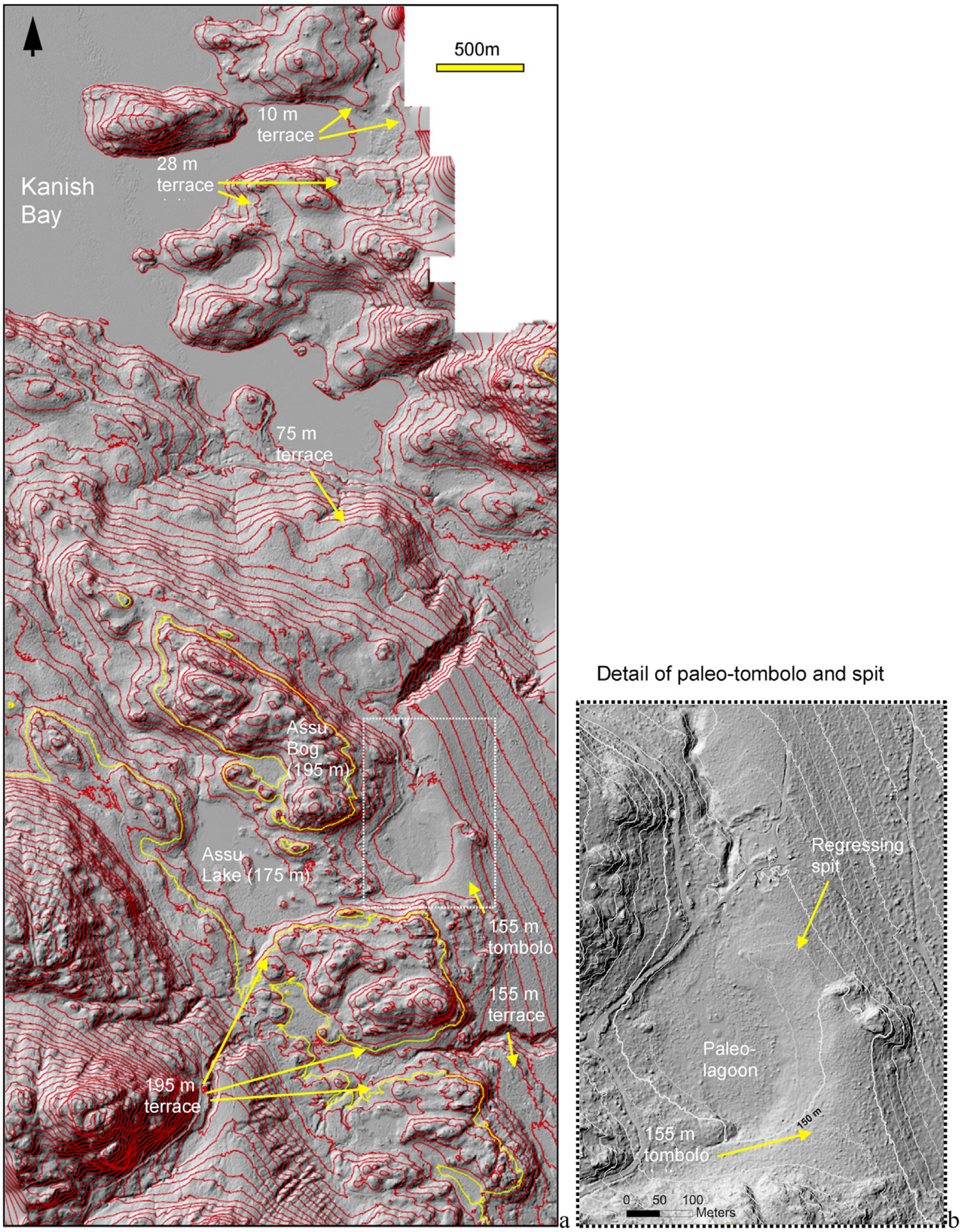

Fig. 5. Assu LiDAR block, per Fig. 2, with 10 m contours (a), and 155 m tombolo detail with 5 m contours (b). Assu Bog and Lake became isolated from the ocean ca. 14,500 and 14,300 years ago respectively. Fig. 2b tombolo dates to between ca. 13,900 and 13,800 years ago per Quadra sea level curve (Fedje et al., 2018, Fig. 3). Base maps prepared by A. Lausanne.

exposed shorelines where longshore drift has access to a substantive sediment supply. These landforms tend to be relatively easy to discern on LiDAR DEMs as they often extend well beyond the main areas of source sediment and generally show marked relief (Fig. 6), however from the Quadra Island DEMs beach ridges are, at most, weakly discernible. This is likely because the LiDAR coverage for Quadra Island is in areas without substantial fluvial sediment supply and mostly encompasses paleo-coastlines which would have ranged from protected to very protected from primary wind fetch. The dense rainforest canopy and uneven terrain, with abundant trees throws and stumps, also makes it more difficult to acquire ground hits from LiDAR and to perform the necessary post-processing steps to create paleo-landscape models. Beach ridge features are quite distinct along the adjacent shoreline on Vancouver Island near Elk Bay where a river flows out onto a semi-exposed paleo-shoreline landscape (Fig. 6). Although these features have relatively high visibility, they tend to have limited archaeological potential as wave exposure results in poor access and relatively low intertidal and marine food resource productivity.

4.6. -Beach berms

Beach berms observed in the LiDAR are relatively low relief landforms behind estuaries and deltas along protected to very protected shorelines. These, often ephemeral, landforms are produced by wave action transporting intertidal sediment to a high tide or supratidal position during storm events (Otvos, 2000). Their position, often on relatively small alluvial-estuarine landforms,

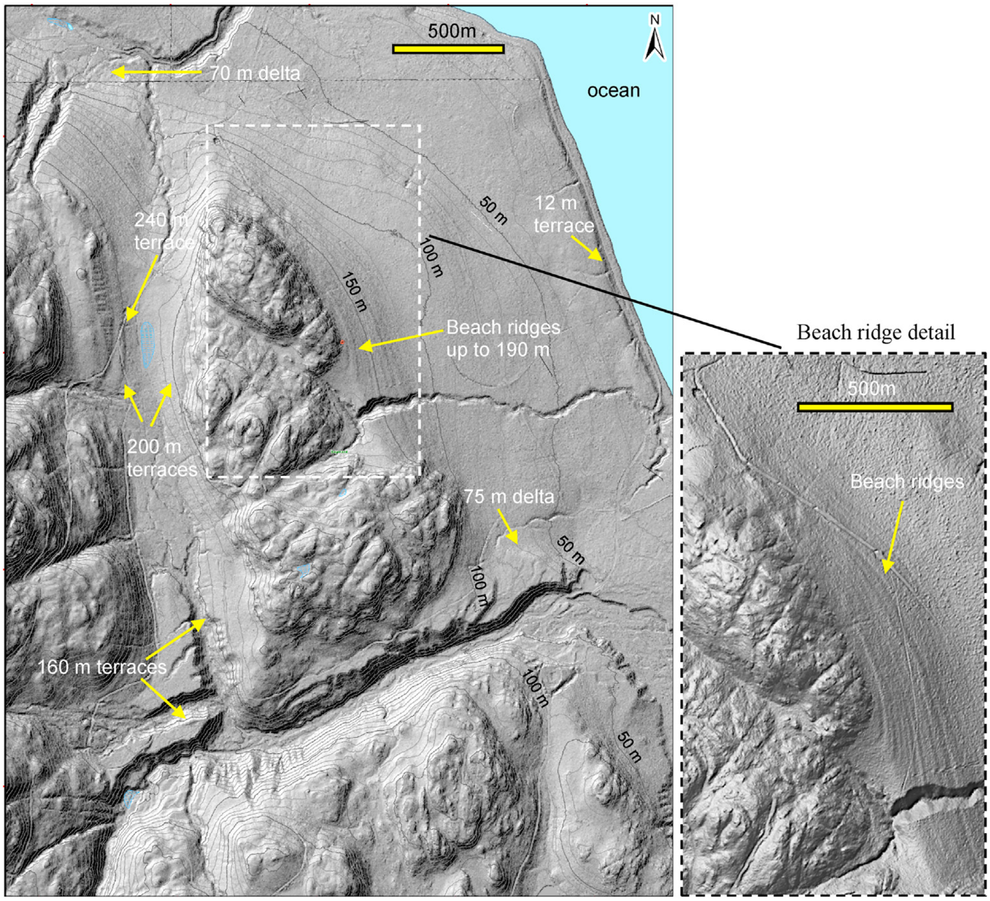

Fig. 6. Elk Bay area LiDAR-derived DEM and detail. The 160 m terrace dates to ca. 13,900 years ago per Quadra sea level curve (Fedje et al., 2018) whereas the 240 m terrace may be the pre-14,300 years ago marine limit. Ten metre contour intervals. LiDAR image (2018) courtesy of Interfor Corporation. The Elk Bay visual highlights paleocoastal features in a LiDAR DEM from a location 5 km west of our study area. Although we did not have access to the raw data, we believe this is a useful supplementary visual representation of paleo coastal features as it illustrates some more well-defined features resultant to a much larger fetch and sediment source than is the case for our Quadra Island study area.

make them difficult to discern on LiDAR, especially as subsequent aeolian and alluvial deposition tends to bury these relatively low relief features (Figs. 7 and 9). However, they will be associated with features such as deltas and beaches which are often visible in LiDAR-derived bare earth models. Supratidal beach berms can have high archaeological site potential as they generally have relatively flat crests, are well drained and can form along protected shorelines (cf. Richardson Island site in Fedje et al., 2004). These supratidal areas would have provided desirable camping and living locations after sea levels fell lower, as they tend to form relatively flat, terraced areas during marine regression.

4.7. -Paleo-tombolos and spits

Paleo-tombolos and spits are visible on LiDAR-generated Digital Elevation Models, as these low relief landforms often protrude out from otherwise steep semi-exposed to protected shorelines (Fig. 5). Often the presence of a bedrock anchor and the unique shape of tombolos makes them easy to discern in LiDAR models. These landforms often have very high archaeological potential as they provide greater intertidal productivity on their lee shores as well as boat access on alternative shores, especially important when access is limited due to wave action from prevailing winds.

5. Paleoshoreline features investigated

Archaeological fieldwork was carried out between 2014 and 2018. LiDAR was obtained in 2014 for East and North Quadra and in 2018 for Elk Bay and Assu uplands (Figs. 5 and 6). Field reconnaissance and ground-truthing LiDAR DEMs through archaeological survey was conducted for East and North Quadra. The Assu area was briefly visited prior to obtaining LiDAR data for that area, but no investigations were conducted following receipt of this data as the archaeological permit had expired. No field investigations were conducted in the Elk Bay area. Information from the latter two areas therefore derives largely from examination of the LiDAR DEMs. Here we summarize paleoshoreline features observed in the LiDAR imagery, note how these may associate with geological events, and, where available, provide examples of archaeological sites associated with these features (Table 1).

Paleoshoreline features at 3–4 m are common. A Pleistocene/Holocene transition example of a beach berm and associated terrace was documented during excavation of a 3 m component of the Yeatman Bay archaeological site (Figs. 8 and 9). The present terrace surface is 4–5 m, as a result of Holocene sedimentation burying the ca. 11,000–10,500-year-old landform. Evidence of a marine transgression and associated berm formation comes from stratigraphy and microfossil analyses (Fedje et al., 2018). A date of 11,300 years ago on charcoal, intertidal microfossils and water-

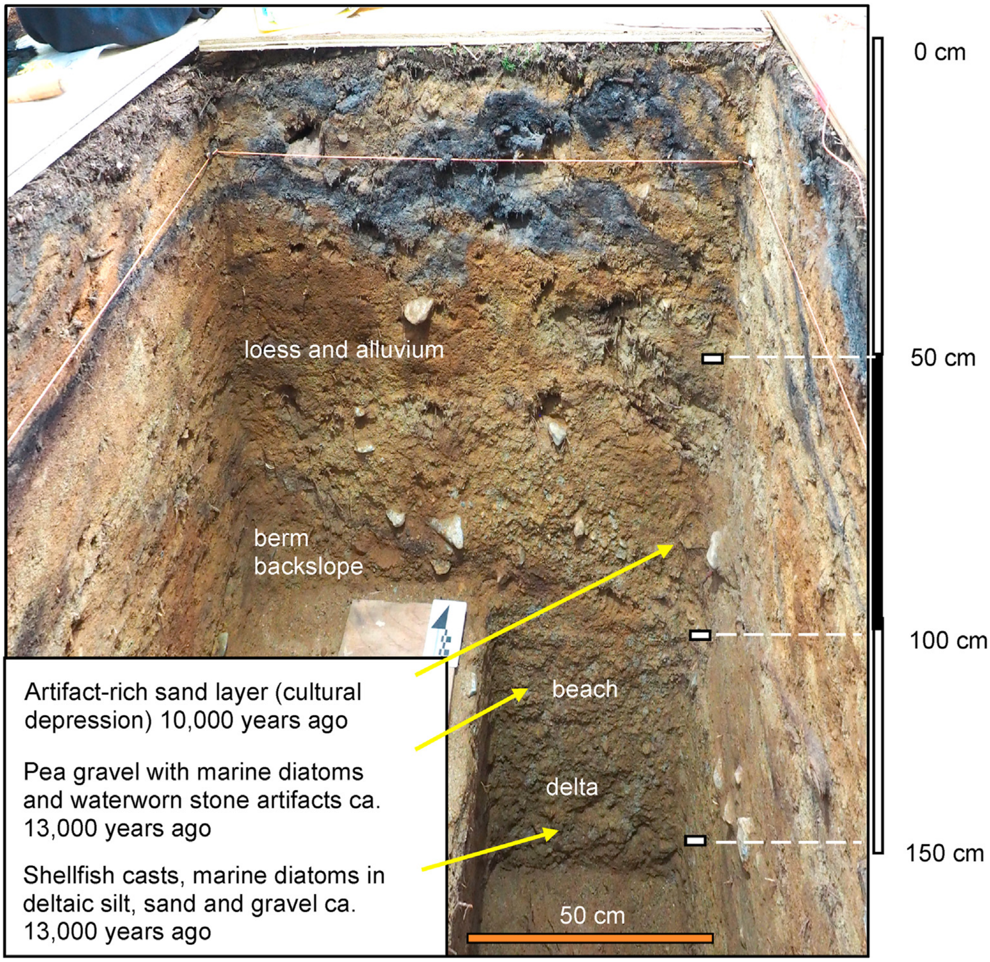

Fig. 7. Lactarius Road EU-1 north wall profile photo showing an example of a buried beach berm. Base of unit is 180 cm below surface. J. McSporran photo.

rounded stone tools (secondary deposition) all appear to correlate with berm formation. The berm is suggested to have formed from erosion and redeposition by wave action of intertidal sediment, including that of a ca. 1 m paleoshoreline, as sea level rose. Overlying the berm deposits are pristine stone tools, terrestrial microfossils and several dates on charcoal ranging from 11,000–10,500 years ago. This evidence appears to represent an (immediately post-transgressive) *in situ* archaeological component. Younger Dryas advances may have slowed sea level fall and contributed to development of the hypothesized ca. 1 m terrace ca. 12,000 years ago. Subsequently, post-Younger Dryas MWP-1b (Abdul et al., 2016), at ca. 11,400–11,100 years ago, correlates with the transgression that formed the 3–4 m berm (Tables 1 and 3).

Terraces at 10–12 m are readily resolvable at many locations in the Quadra Island LiDAR DEMs. The age of this terrace fits well to the timing of the 12,800–12,550 years ago meltwater pulse (Table 1). On LiDAR they show as strong breaks-in-slope backed by low relief alluvial fans. The Crescent Road (Fig. 10) and Yeatman Bay (upper terrace, Fig. 8a and b) archaeological sites provide good examples of these features. At both sites, excavations encountered deltaic sediment at ca. 2.0 m depth (Fedje et al., 2018; Lausanne, 2018; Lausanne et al., 2019). This sediment contained intertidal and nearshore marine microfossils (diatoms) and macrofossils (shellfish casts) as well as charcoal dating to ca. 12,800 years ago. Water rounded stone artifacts, indicating secondary deposition, were also recovered from these intertidal sediments. The archaeological results, stratigraphy and marine fossils provide evidence for a marine transgression that aligns with the local sea level curve and the globally recorded meltwater event.

Terraces at 26–28 m are evident at many locations on Quadra Island DEMs. Examples of this terrace include the Kellerhals gravel pit (Fig. 11), the Lactarius Road archaeological site (Fig. 12) and several terraces in the Kanish Bay area (Fig. 5; Fedje et al., 2016, 2018, 2021; Lausanne et al., 2019). These terraces have not been radiocarbon dated but are estimated to date to ca. 13,000–12,900 years ago with reference to isolation basin coring results used to create the Quadra sea level curve (Fedje et al., 2018). The sea level-based age range fits well to the timing of the 13,150–12,900 years ago meltwater pulse (Tables 1 and 3).

Terrace features at ca. 75–80 m are observable in both the Quadra and Elk Bay DEMs. Well-defined deltas are evident at 75 m at Elk Bay and 75 m terraces front towards Kanish Bay (Figs. 5 and 6). These features have not been directly dated but are estimated to date to ca. 13,300 years ago with reference to the Quadra sea level curve. This would be close to the timing of the 13,500–13,300 years ago meltwater pulse (Tables 1 and 3). No landforms at this elevation were subject to archaeological survey.

Paleomarine landforms, including terraces, spits and tombolos are clearly evident at 155–160 m elevation in Quadra and Elk Bay DEMs. Near Assu Lake (Fig. 5) these landforms are at ca. 155 m asl while at Elk Bay (8 km westerly) strongly developed terracing is evident at 160 m asl (Figs. 5 and 6; Fedje et al., 2018, 2021; Lausanne et al., 2019). These features remain undated, but the elevation cross-dates the feature to ca. 13,800 years ago using the

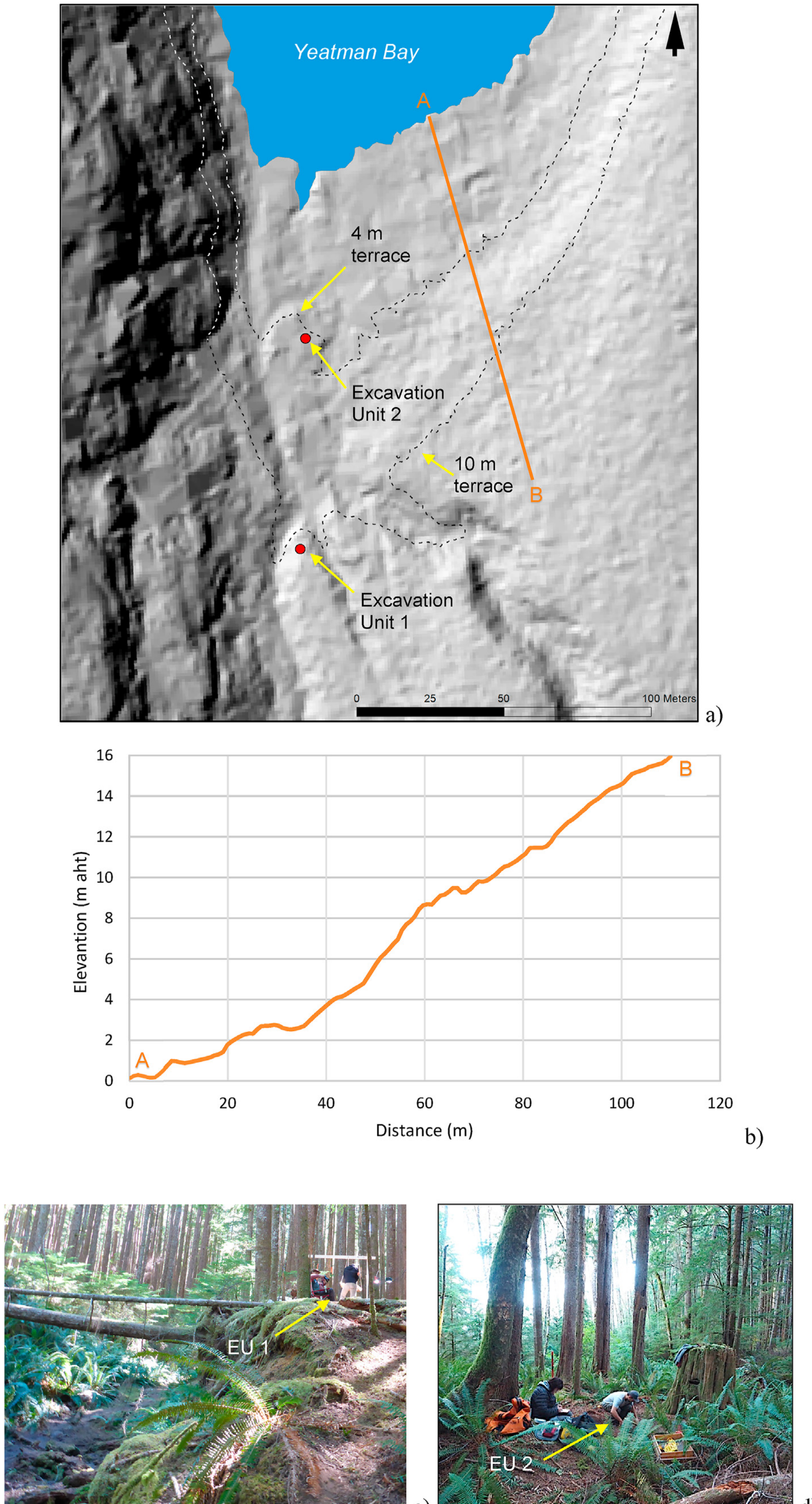

Fig. 8. a) Yeatman Bay LiDAR detail. The 10 m terrace dates to ca. 12,700 years ago, 4 m terrace dates to ca. 11,000 years ago). Red dots mark location of archaeological excavation units, 1 m contour interval and location of shoreline profile shown in orange. Base map prepared by Alex Lausanne from LiDAR data collected by Hakai Institute; b) shoreline profile showing breaks in slope at 4 m and 10 m aht; c) Excavation Units on 10 m (EU1) and 4 m (EU2) terraces. J. McSporran photos. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 9. Stratigraphic profile of east wall of Excavation Unit 2 at Yeatman Bay (a), projectile point base from sandy pea-gravel layer (b, c), shellfish cast (*Clinocardium nuttallii)* from silty sand at base of excavation (d). J. McSporran photos.

Quadra sea level curve. This terrace elevation has not been investigated archaeologically. The age of this terrace fits well to the timing of the 13,800–13,650 years ago meltwater pulse (Tables 1 and 3).

Terrace features at 195–200 m are observable in the Quadra and Elk Bay DEMs (Figs. 5 and 6). These do not seem to be as well developed as those at 150–155 m elevation. Terraces at ca. 195 m can be seen in the Assu Lake area and at ca. 200 m in Elk Bay (Figs. 5 and 6; Fedje et al., 2018, 2021; Lausanne et al., 2019). These features have not been directly dated but are estimated to date to ca. 14,250 years ago with reference to the Quadra sea level curve. This aligns with the early Sumas advance and is close to the timing of the 14,150–14,050 years ago meltwater pulse (Tables 1 and 3). A few of the terraces at this elevation were subject to archaeological testing, but no sites were identified.

A well-developed terrace is evident at 240 m in the Elk Bay LiDAR DEM (Fig. 6). This terrace may represent the marine maximum for this region. The feature is above the limit of the Quadra sea level curve and has not been dated. No fieldwork was carried out at this location. Terrace development could relate to a slowstand or transgression associated with the ca, 14,500–14,200 years ago MWP-1a event. Support for this interpretation may be seen in data for the outer BC Central Coast where rapid sea level rise ca. 14,500 years ago (McLaren et al., 2014) post-dates glacial recession (Darvill et al., 2018) but fits well to MWP-1a timing (Abdul et al., 2016; Blanchon et al., 2021; Fairbanks, 1989).

A number of terrace features are evident at elevations other than those included here but are generally less well-defined or more limited in extent. Further LiDAR analysis and field investigations would be needed to better define these terraces. They may be associated with local phenomena such as tectonic or isostatic events or with minor global meltwater pulse events not captured by Khanna et al. (2017).

6. Archaeological evidence for paleoshorelines

In addition to the data obtained from excavations at the Yeatman, Crescent and Lactarius sites, a number of other archaeological sites are situated in proximity to paleoshoreline features and several of these produced waterworn artifacts, indicative of marine processes. We summarize archaeological components associated with the ca. 3 m, 12 m and 28 m paleoshorelines that contain waterworn chipped stone artifacts (Table 2). We suggest that these components can be cross dated using the Quadra sea level curve.

7. Discussion

7.1. -Paleo-ecolandscape evolution

The stranded paleoshoreline features described here likely developed during periods of relatively stable shorelines and appear to be associated with climatic events such as local glacier advances (potentially resulting in renewed isostatic depression) or periods of rapid global eustatic rise that, together, would have slowed local

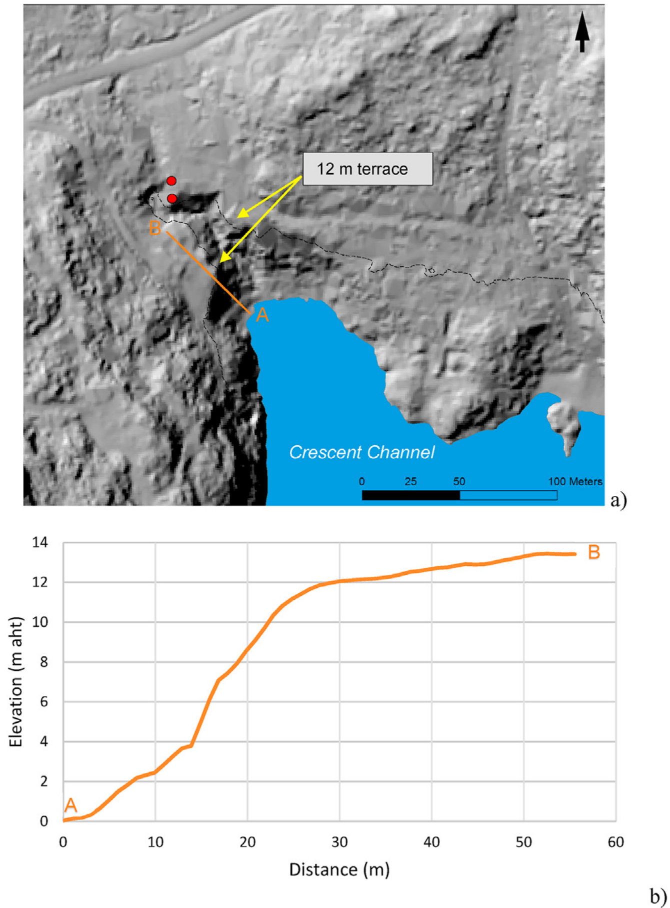

Fig. 10. Crescent Road site 11–12 m terrace dates to ca. 12,700 years ago (Fedje et al., 2018). Red ellipses mark archaeological excavation unit locations and location of shoreline profile shown in orange. Base maps prepared by Alex Lausanne from LiDAR data collected by Hakai Institute in 2014; b) shoreline profile showing break in slope. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sea level regression. Examination of current data, with reference to timing of these events suggests that eustatic events may have been the main factor resulting in the stillstands, slowstands and minor transgressions observed on Quadra Island. The ages obtained for six intervals of paleoshoreline (3–5 m, 10–12 m, 26–28 m, 70–75 m, 150–155 m and 195–200 m) near Quadra match well to the ages of marine terraces associated with periods of rapid global sea level rise (Table 1 and 3; Fig. 13; Abdul et al., 2016; Blanchon et al., 2021; Khanna et al., 2017). These terraces may be a consequence of a sequence of rapid sea level rises briefly counteracting ongoing rapid local isostatic crustal uplift between ca. 14,500 and 11,000 years ago.

Meltwater pulses 1a and 1 b are thought to be events that rose eustatic sea level by 10 m or more while the intermediary pulses were in the order of 2–4 m (Abdul et al., 2016; Blanchon et al., 2021; Deschamps et al., 2012; Khanna et al., 2017). The effect of these global sea level rise pulses is lessened on Quadra because they were buffered by isostatic rebound. There are no paleoecological records in the Quadra area early enough to connect to MWP-1a although a prominent terrace at 240 m elevation at Elk Bay could date to this time. A transgressive sequence identified at nearby Village Bay Lake (Fedje et al., 2018) suggests a marine transgression of 2–3 m at ca. 11,450 years ago. This would fit well to the large MWP-1b pulse and the proposed marine transgression at Yeatman Bay. Meltwater pulses occurring between ca. 14,400 and 11,500 years ago appear to have resulted in rapid global RSL rises in the order of 2–4 m (Khanna et al., 2017). On Quadra Island these smaller pulses resulted in stillstands or slowstands but may not have counteracted ongoing isostatic uplift sufficiently to result in marine transgressions.

Overall, there appears to be a fairly close concordance between interstadial onsets or warming events such as those inferred from electrical conductivity and ^{18}O measurements from the NGRIP and GISP2 the Greenland Ice Sheet cores (Taylor et al., 1993; Johnsen et al., 2001) and Chinese ^{18}O isotope speleothem records (Wang et al., 2001), and the development of coastal terraces, both on Quadra Island (as presented here) and in the Gulf of Mexico (Fig. 13; Khanna et al., 2017). Possible reasons for imperfect concordance are many, including global climate conditions needing to be warm for a prolonged period so as to melt enough ice to increase the volume of water in the ocean, delayed glacial lake outburst floods (Iturrizaga, 2011) and radiometric uncertainties. The formations of deltas, spits, estuaries and tombolos seen on Quadra Island would presumably have also taken some time to develop once sea level regression slowed or was reversed as eustatic rise approached or outpaced isostatic rebound.

7.2. -Archaeology

On the Northwest Coast there are very few archaeological sites dating earlier than ca. 11,000 years ago (Mackie et al., 2011; McLaren et al., 2019). This is in large part a consequence of a very dynamic sea level history (e.g., Fig. 3) and the challenges of identifying early post-glacial shorelines. The approach described here

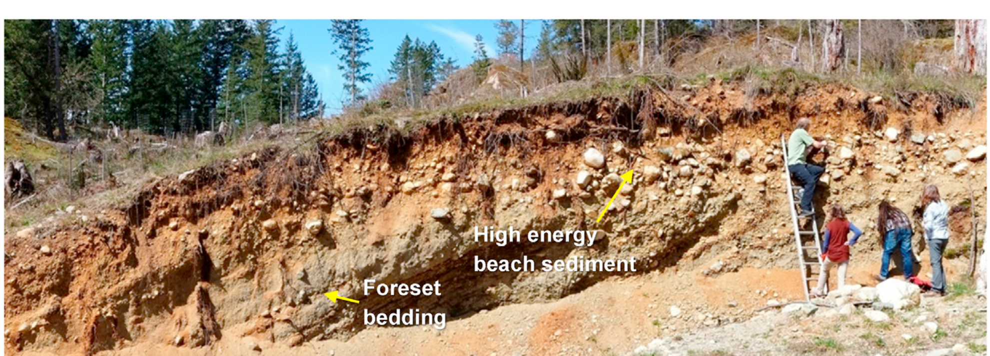

Fig. 11. Marine terrace profile at Kellerhals gravel pit showing foreset beds (with abundant shellfish casts) on left and high energy beach deposits on right. Terrace elevation is 28 m. Paul Bishop photo.

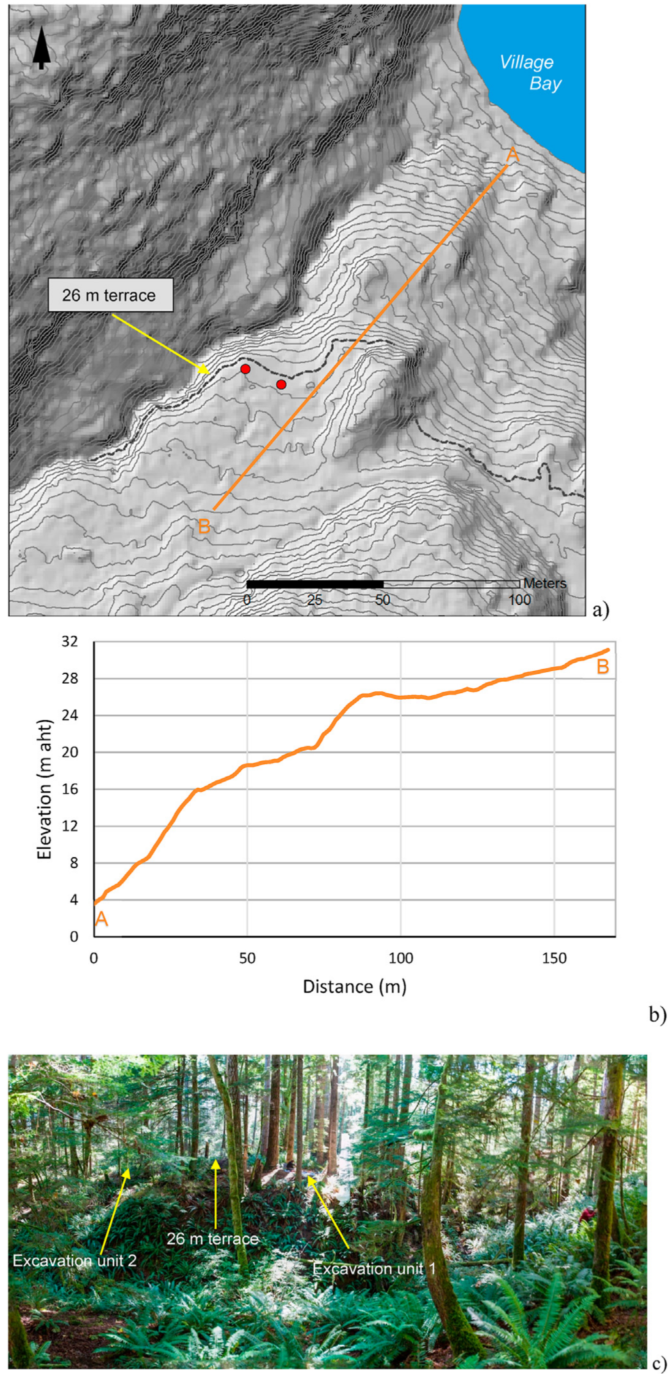

Fig. 12. a) Lactarius site LiDAR detail. 26 m terrace dates to ca. 13,000 years ago Red ellipses mark archaeological excavation unit locations and location of shoreline profile shown in orange. Base maps prepared by Alex Lausanne from LiDAR data collected by Hakai Institute in 2014; b) shoreline profile showing 26 m break in slope and terrace; c) 26 m terrace and archaeological excavation locations. Al Mackie photo. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

results in much increased efficiencies in the prediction of areas with high potential for location of early post-glacial archaeological sites. Narrowing target areas for archaeological prospection to just those with well-defined marine shorelines reduces prospective survey areas from hundreds of square kilometers of regressive shorelines (all lands from 200 m to one or 2 m above the modern shore) to a few tens of square kilometers of relatively stable paleomarine features. Concomitantly, the potential for decades of human occupation and deposition of cultural artifacts at such specific locations greatly increases the likelihood of field surveys intersecting early archaeological sites. Following this approach, the relatively small-scale inventory conducted on Quadra Island identified at least 20 early post-glacial archaeological sites. Prior to this work no early prehistoric sites were known for Quadra Island and environs.

8. Conclusions

Quadra Island investigations have produced evidence of sea level stillstands, slowstands and marine transgressions which has enhanced the visibility of parts of the early archaeological record of the area. The Quadra sea level curve, as with other curves developed for the Northwest Coast, is based on a relatively small number of data points. It is a good proxy for the general timing of marine regression but does not have sufficient detail to isolate brief intervals of shoreline stability that could be key to increased visibility of any associated archaeological record. As existing sea-level records do not have the ability to resolve these smaller amplitude variations it is pertinent to investigate geological records that directly document spatiotemporal sea level changes to determine if decadal to century-scale slowing of sea-level regression is a common occurrence. Here we have employed LiDAR derived DEMs to identify paleoshoreline features indicative of such events. The presence, observability, and remote identification of potential paleo-coastal features from LiDAR-derived models has helped to highlight key areas of high archaeological potential at (now) inland and elevated locations. Together, LiDAR and sea level histories can identify those paleoshorelines that will have higher visibility and, hypothetically, higher archaeological potential. Once target shorelines are identified, predictive modelling (Lausanne, 2018; Lausanne et al., 2019; Vogelaar, 2017) can increase efficiencies in archaeological site prospection.

Terraces and other paleoshoreline features appear to track minor and major meltwater pulses, which is an advantage of working in these rapidly regressing contexts. This is significant because it is a general principle that can be drawn upon to guide archaeological prospection in other rapidly regressing contexts and, provides a fourth pillar to the GISPO18, GDRIP-ECM, and Coral U-th methods. By tying these paleoshoreline features into global, multiple proxy assessments of sea level change we increase the confidence in the formation dates of the terraces and their origins. As a result, proxy evidence such as the waterworn artifacts become much more of a smoking gun, allowing us to apply the Norwegian method of cross dating from RSL to archaeology (Bjerck, 2009; Breivik, 2014; Svendsen and Mangerud, 1987).

On Quadra Island a number of sites appear to be associated with raised beaches, formed by marine transgressions, stillstands or slowstands, suggesting the possibility of elevation-based dating relative to the known history of relative sea level (Fedje et al. 2018, 2021). However, raised shoreline features might be expected to be used as campsites for centuries or millennia subsequent to sea level regression as long as they remained in relative proximity to the ocean shore. Support for association of archaeological sites with paleoshorelines includes the aforementioned micro and macrofossil data and the presence of water-rolled artifacts in the archaeological assemblages.

Together these data provide direction for increasing the potential for discovery of early post-glacial archaeological sites in the Quadra area and, by extension, in other parts of the Northwest Coast subject to rapid marine regression. Marine regression may leave much of the record of human history for this early time sparsely stranded in the coastal rainforest, but intervals of relative

Table 1
Quadra area paleoshoreline features and geological events (in cal years BP).

Terrace elevation	Sea level intercept	Archaeological sites noted in text	Meltwater pulse[c]	Glacial advance[d]
3–5 m	11,400	Yeatman Bay (EbSh-98)	11,300–11,100 (MWP-1b)	
10–12 m	12,700	Crescent Road (EbSh-81) Yeatman Bay (EbSh-98	12,800–12,550	ca. 12,800–11,500
26–28 m	13,000	Lactarius Road (EaSh-81)	13,150–12,900	
75 m[a]	13,300	Not surveyed	13,550–13,300	ca. 13,500–13,200
150–155 m	13,750	Not surveyed	13,800–13,650	
195–200 m	14,250	Brief survey, no sites	14,150–14,050	
230–240 m[b]	n/a	Not surveyed	14,500–14,200 (MWP-1a)	ca. 14,500–14,000

All sites were located and recorded by the DILA archaeological team.
[a] 75 m terrace tentatively identified from Quadra LiDAR and as delta and terraces on Elk Bay LiDAR (Figs. 5 and 6).
[b] Maximum marine transgression not observed on Quadra Island. The 240 m terrace nearby at Elk Bay (Vancouver Island) may be the early post-glacial marine maximum.
[c] Meltwater pulse per Abdul et al., 2016; Blanchon et al., 2021; Khanna et al., 2017.
[d] Friele and Clague 2002; Menounos et al., 2009.

Table 2
Quadra DILA project archaeological components with waterworn chipped stone artifacts (not including lakeshore sites). Note that the Lactarius (EaSh-81), Crescent (EbSh-81 and Yeatman (EbSh-98) sites are briefly discussed above.

Archaeological site and elevation grouped by terrace age	Depth of basal component	Artifact count: waterworn/ total[c]	Depositional context	Artifact recovery
3-5m 11.5–10 kya[a]				
EaSh-75 – 4 m	>40 cm	13/14	Marine terrace - sand and gravel	Excavated Excavated
EaSh-75 – 5 m	>40 cm	6/186	Paleo-tombolo - sand and gravel	Excavated Excavated
EaSh-76 3 m	>40 cm	202/442	Beach berm - sand and gravel	Excavated
EbSh-23 5 m	n/a (tests)	2/43	Marine terrace - sand and gravel	Surface and excavated
EbSh-82 5 m	>20 cm	32/78	Beach berm – sand, gravel, pebble 1	Excavated
EbSh-95 5 m	n/a (tests)	7/59	Marine terrace- sand and gravel	Excavated
EbSh-98 4 m	>120 cm	11/142	Beach berm - sand, gravel, pebbles	Excavated
8–12m ca. 12.7 kya				
EbSh-6 10 m	n/a (test)	1/4	Marine terrace – sand and gravel	Surface and excavated
EbSh-80[b] 8 m	>60 cm	29/46	Beach - sand, gravel and pebbles	Excavated
EbSh-81[b] 11 m	>110 cm	8/30	Delta - sand and silt	Excavated
EbSh-93 10 m	n/a (tests)	5/29	Marine spit and terrace -sand and gravel	Surface and excavated
EbSh-95 12 m	n/a (test)	2/8	Marine terrace - sand and gravel	Surface and excavated
EbSh-98[b] 12 m	>60 cm	1/71	Beach berm - sand and gravel	Excavated
26–32m ca.13.0 kya[a]				
EaSh-92 29 m	n/a (test)	1/2	Marine terrace - sand and gravel	Excavated
EaSh-88 27 m	n/a (test)	3/8	Paleo-tombolo - sand, gravel and pebbles	Excavated
EaSh-81[b] 26 m	>100 cm	12/77	Beach berm - sand and gravel	Excavated
EbSg-25 26 m	n/a (tests)	3/15	Beach berm - sand and gravel	Surface and excavated
EbSg-26 26 m	n/a (tests)	2/11	Marine terrace – sand and gravel	Surface and excavated
EbSh-94 30 m	n/a (tests)	1/18	Beach berm and marine terrace – sand and gravel	Excavated
EbSh-97 30 m	n/a (test)	1/23	Marine terrace - sand, gravel and cobbles	Surface and excavated
EbSh-99 27 m	n/a (test)	1/2	Marine terrace – sand and gravel	Surface and excavated
EbSh-102 26 m	n/a (test)	2/3	Marine terrace – sand and gravel	Surface and excavated
EbSh-106 27 m	n/a (test)	2/6	Paleo-tombolo - sand and gravel	Surface and excavated
EbSh-107 31 m	n/a (tests)	7/17	Marine terrace – sand and gravel	Surface and excavated
EbSh-108 32 m	n/a (test)	1/3	Marine spit - sand and gravel	Surface and excavated

All sites were located and investigated by the DILA archaeological team between 2014 and 2017.
[a] Ages of respective terraces (not necessarily age of basal archaeological component).
[b] One or more 0.5 m^2 or larger evaluative unit (excavated down to beach or deltaic sediments).
[c] Counts and sediment descriptions are for basal components only.

Table 3
Comparison of ages for Gulf of Mexico and Quadra Island terraces.

Gulf of Mexico (marine terrace)		Quadra Island (terrestrial terrace)		
Paleo terrace depth (m)	Inferred age range from paleo terrace depth (cal years BP)	Terrace elevation (m aht)	Inferred age range from paleo terrace elevation - sea level history intercept (cal years BP)	Tentative Interpretation
61.6 ± 2.1	12,400–11,200	3–4	ca 11,400	transgression
65.6 ± 1.2	12,800–12,550	10–12	ca.12,700	stillstand
69.2 ± 1.7	13,150–12,900	26–28	ca. 13,000	stillstand
73.3 ± 1.7	13,550–13,300	75–80	ca.13,300	stillstand
76.8 ± 1.1	13,800–13,650	155–160	ca.13,800	stillstand
84.9 ± 1.6	14,150–14,050	195–200	ca. 14,250	slowstand
97.0 ± 1.6	14,550–14,450	~240	>14,250	transgression

Gulf of Mexico data from Khanna et al., (2017).
Transgressive terraces formed when eustatic sea level rise briefly surpassed isostatic rebound; stillstand terraces formed when eustatic and isostatic processes were equal, and slowstand terraces are weakly developed terraces formed when the rate of eustatic rise approached isostatic rebound.

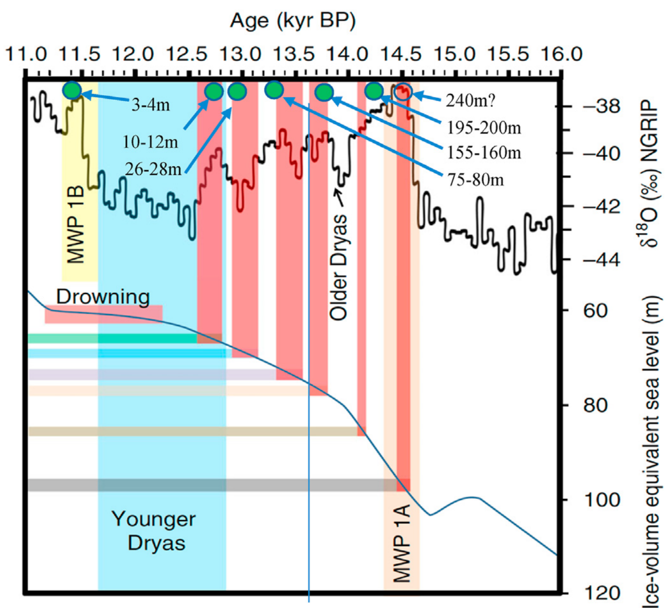

Fig. 13. Times of global sea level rise (dark blue line), meltwater pulses (orange rectangles) and NGRIP ^{18}O (warm periods – black line) from Khanna et al., (2017) (with permission) and, marine terrace elevations and rsl intercepts for Quadra Island (green circles). The 240 m terrace is not constrained by the Quadra sea level curve. It is estimated to date to ca. 14,500 years ago based upon data from the BC Central Coast (McLaren et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

shoreline stability may significantly heighten archaeological visibility as identifiable shorelines with their concomitant potential for greater density of archaeological evidence become more visible.

Quadra Island was deglaciated relatively late and this approach could, at most, push back the archaeological record to ca. 14,500 years ago. Applying the Quadra method to areas deglaciated earlier, such as Victoria which was ice-free by 15,700 years ago (Clague and James, 2002) and the outer coasts of northwest Vancouver Island and the B.C. Central Coast, which were ice-free by 18,000 years ago (Darvill et al., 2018; Hebda, 2019), could help identify records key to earliest human occupation of the Northwest Coast.

Author contributions

Daryl Fedje – primary investigator, research design, field work, analysis, author, editing. Alex Lausanne – field work, GIS, author, editing. Duncan McLaren – field work, corresponding author, editing. Quentin Mackie – field work, author. Brian Menounos – LiDAR, author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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