



## A revised sea level history for the northern Strait of Georgia, British Columbia, Canada



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### ARTICLE INFO

#### Article history:

Received 1 February 2018

Received in revised form

6 May 2018

Accepted 13 May 2018

Available online 13 June 2018

### ABSTRACT

A refined relative sea level (RSL) history spanning the past 14,300 calendar years is described for the Quadra Island area in the northern Strait of Georgia on the Pacific coast of Canada. Here marine shorelines dating to the time of earliest post-glacial emergence are at least 197 m above present-day sea-level at 14,300 years ago. RSL fell rapidly, reaching two to three metres above present-day by 12,000 years ago. A series of raised marine terraces at ca. 4, 10 and 30 m above present day high tide level suggest the rapid fall in RSL during early post-glacial time may have been briefly interrupted by factors such as regional ice advances and recessions and global meltwater pulses generated by climatic variations. A possible minor sea-level transgression of 1–2 m around 12,000 to 11,400 years ago was followed by slow regression to modern levels. This sea-level reconstruction is providing critical input for efficient discovery and cataloging of late Pleistocene and early Holocene archaeological sites on ancient raised shorelines in the region. Integration of the sea-level history with LiDAR imagery has proven successful in locating a number of archaeological sites on these ancient shorelines.

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## 1. Introduction

The relative sea level (RSL) history of coastal British Columbia varies greatly from one location to another because of spatially variable vertical land displacements that occurred in response to glacial ice loading and unloading of the Earth's crust. Beneath an ice sheet, the surface of the Earth is depressed due to flow in the Earth's mantle, while at the periphery of a large ice load the land rises. Upon deglaciation, the depressed regions rise, while peripheral regions subside. The process, termed glacial isostatic adjustment (GIA), generated large vertical land displacements in British Columbia with significant spatial variability (Mathews et al., 1970; Clague et al., 1982; Clague and James, 2002). Consequently, Late Pleistocene and Holocene sea-level histories differ greatly from one location to another in coastal British Columbia (e.g., Shugart et al.,

2014). A previously developed RSL history for the northern Strait of Georgia (James et al., 2005) provided the general features of postglacial sea-level change. It featured a rapid sea-level fall from a high-stand, but was not well constrained during the early Holocene.

Under the auspices of the Discovery Islands Landscapes Archaeology (DILA) program sponsored by the Hakai Institute, new field investigations described here further refine the history of RSL change on Quadra Island. We demonstrate how the resulting RSL curve has helped guide archaeological investigations, especially for early period archaeological sites.

### 1.1. Regional setting

This research focuses on the Discovery Islands, which lie between the British Columbia mainland and Vancouver Island at the north end of the Strait of Georgia. These islands mark the transition from the open waters of the Strait to the network of marine channels and fjords that comprise Johnstone Strait to the north. The

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Coast Mountains to the east rise up to 4000 m while the Vancouver Island Ranges to the west rise to a maximum elevation of ca. 2000 m. Southern Quadra Island exhibits relatively little relief with elevations to ca. 100 m while northern Quadra Island is characterized by rocky shorelines and greater relief with elevations to ca. 600 m. The area is located in the Coastal Western Hemlock biogeoclimatic zone (Meidinger and Pojar, 1991).

## 1.2. Glacial history

At the end of the Olympia Interstadial (MIS 3 – ca. 56,000 to 30,000 years ago), the Cordilleran Ice Sheet advanced into the northern Strait of Georgia (Clague and James, 2002; Hebda et al., 2016). In the Strait of Georgia area, the maximum extent of Fraser Glaciation (MIS 2) ice occurred approximately 17,000 to 16,000 years ago, after which there was rapid retreat (Clague et al., 1997; Clague and James, 2002).

Several glacial re-advances occurred in this area over the following millennia, including during the Older Dryas, the inter-Allerod cold period and the Younger Dryas (Clague et al., 1997; Clague and James, 2002; Eamer et al., 2017; Menounos et al., 2009). In the region of the Discovery Islands recent work by Mood and Smith (2015) documents a Younger Dryas age advance dating from about 12,900 to 12,700 years ago at the Franklin Glacier (ca. 90 km north of Quadra Island) as well as a series of later Holocene advances, some of which extended into the Georgia Basin lowlands (see also Clague and James, 2002; Menounos et al., 2009). Further south, Friis and Clague (2002) document a late Younger Dryas advance near Vancouver, BC, dating to after 12,600 years ago. Although the timing and extent of these glacial advances are not all firmly constrained, they may have had an effect on the local sea level history. Events such as local glacial loading and unloading (Clague and James, 2002) and global meltwater pulses (Khanna et al., 2017) may have resulted in brief RSL stillstands or minor transgressive events that generated paleo-shoreline features which, in turn, provide targets for investigating the early archaeological record.

## 1.3. Regional sea level

During the last glacial maximum (LGM) global sea level was about 120 m below present because ocean water was trapped on land in the form of ice sheets and glaciers (e.g., Peltier and Fairbanks, 2006). Following the Last Glacial Maximum, global eustatic sea-level rise commenced as continental ice sheets started to lose mass and deglaciation started. For most areas distant from glaciers and ice sheets, eustatic sea-level rise resulted in glacial-age ocean shorelines becoming deeply drowned. In many high latitude regions, however, relative sea level history was strongly affected by the interplay between this eustatic change and vertical land motion, due to both glacial isostasy and active tectonics. Along the Pacific coast of Canada, late Pleistocene shoreline elevations are highly variable as the earth's crust responded to the thinning and retreat of the Cordilleran ice sheet following the LGM (e.g., Clague et al., 1982; McLaren et al., 2014; Shugar et al., 2014, Fig. 2). For example, on Haida Gwaii, early post-glacial shorelines are up to 150 m lower than modern levels due to a glacial forebulge (Clague, 1983; Josenhans et al., 1997) while shorelines of the same age, in areas that were subject to substantial isostatic depression, are at 200 m elevation or more along parts of the inner coast (Clague et al., 1982; Fedje et al., 2005; Shugar et al., 2014). RSL in coastal British Columbia varies strongly in both the east to west and north to south directions and depends on the size, timing, and location of glacial loading and unloading.

## 1.4. Previous sea level research in the Discovery Islands

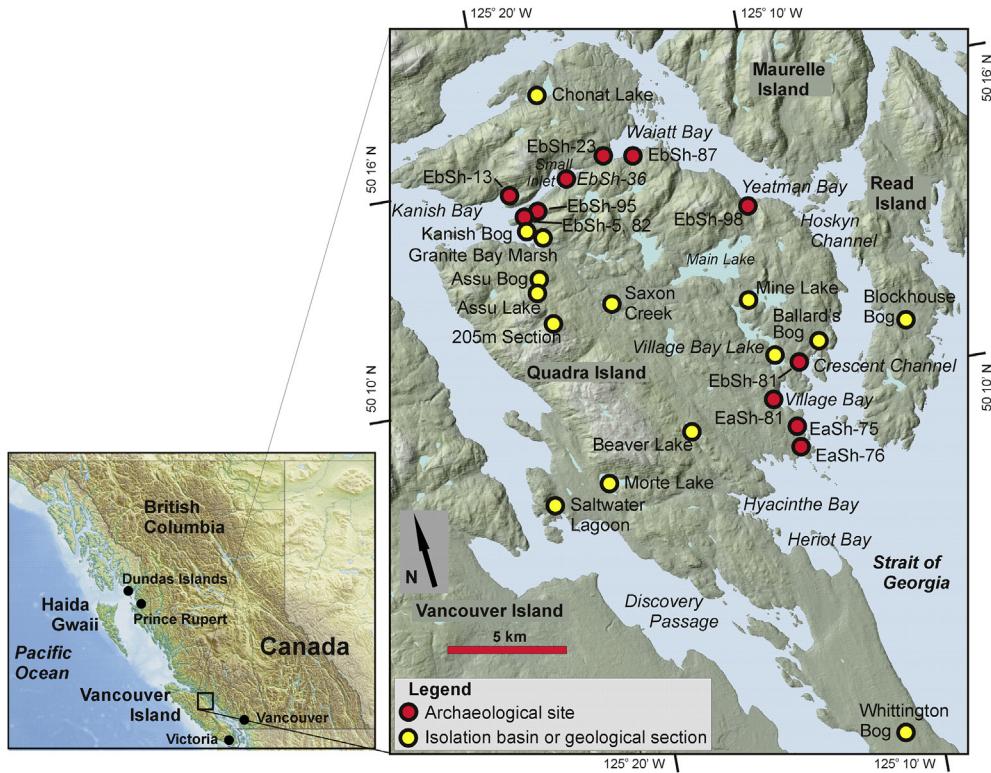
A relative sea-level history for the Quadra Island environs is given by James et al. (2005) (Fig. 3). An upper marine limit of about 175 m elevation was identified (McCammon, 1977), but its timing and duration was not known. Sea-level fell to 145 m by about 13,750 years ago, and was followed by a rapid decline to about 50 m by ca. 13,000 years ago and 23 m elevation by about 12,500 years ago. A number of marine shell ages and knowledge of lowstands to the south (Hutchinson et al., 2004a; James et al., 2002) loosely constrained a possible shallow subtidal lowstand in the Quadra area. The lowstand was followed by a recovery in sea-level to about +1.5 m elevation by ca. 2000 years ago. The inferred RSL curve mapped out the general pattern of sea-level history, especially the early rapid emergence, but there were no direct constraints on sea-levels between 23 m and 1.5 m elevation. The estimated lowstand was hence the most poorly constrained part of their curve. The data presented in this paper refine the rapid late Pleistocene sea-level fall and provide evidence that the lowstand likely did not drop below modern levels.

## 2. Methods

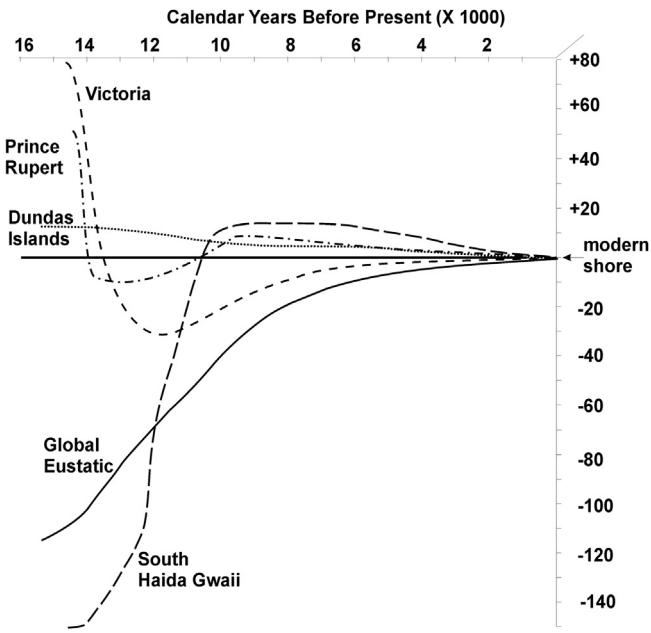
Dated organic material having a recognized relationship to past sea-level (below, within tidal range, above) provide constraints for a relative sea-level curve. Observations and organic samples were collected from freshwater and marine isolation basins, relict shorelines (raised beaches, deltas, etc.) and shoreline proximal cultural features, such as archaeological sites. This study uses data from locations within 5 km of the northwest-southeast axis of Quadra Island (parallel to trend of eastern Vancouver Island) to limit the effect of east-west differences in glacial ice loading and unloading (cf. McLaren et al., 2014). For consistency, all sample elevations have been adjusted to higher high tide (hht), which ranges from four to five and a half metres above Chart Datum (see Appendix 1 footnote). Elevation accuracies (Appendix 1) range from ca. 2 m (barometric altimeter, for locations outside of LiDAR coverage) to 0.25 m for shore proximal data points (laser range finder), adjusted to the elevation of the barnacle line following Plafker (1969). LiDAR imagery acquired for the Hakai Institute has an accuracy of 25 cm, while real-time kinematic (RTK) GPS surveys (Fedje et al., 2016; Holmes, 2015) have accuracies of 0.1–0.4 m. All elevation measurements are given as metres above (ahht) or below (bhht) higher high tide. In inferring a refined RSL curve, we assume that tidal ranges on Quadra were similar to present-day (4–5.3 m, see Appendix 1, footnotes) although, since there were fewer constrained channels associated with much higher sea levels in the Late Pleistocene (e.g. 13,300 to 14,300 years ago) tidal ranges may have been less spatially variable and similar to the ca. 4.8 m range of the open waters of the northern Strait of Georgia.

### 2.1. Isolation basin coring

Isolation basins are basins that undergo marine sedimentation when submerged in the ocean, and that undergo freshwater sedimentation when they rise above sea level and are 'isolated' from the ocean. Coring of isolation basins and radiocarbon dating of the transition from marine to fresh water conditions in the cores provide important constraints on sea-level history. Depending upon the nature of sediments (e.g. coarse sediment, dense clay, gyttja), a variety of devices were employed to core isolation basins. For loose to moderately firm organic or mineral-rich sediment, a 4-cm diameter stainless steel Livingstone or 10 cm diameter polycarbonate Bolivia piston corer (Myrbo and Wright, 2005) was used. When coring devices could not penetrate coarse or very dense



**Fig. 1.** Maps showing (a) the location of the Discovery Islands in coastal British Columbia, Canada and (b) sea-level sites on Quadra and Read Islands.



**Fig. 2.** Selected British Columbia sea level curves for Victoria (James et al., 2009a; Fedje et al., 2009), Dundas Island Archipelago (McLaren et al., 2011), Prince Rupert (Letham et al., 2016) and southern Haida Gwaii (Fedje et al., 2005). The global eustatic sea-level, as approximated by the Barbados sea-level curve, is also given (Peltier and Fairbanks, 2006).

material, a 10-cm diameter PVC tube (cf. Reasoner, 1986) or 3 cm stainless steel EPS corer (Billets, 1998) was driven into the sediment.

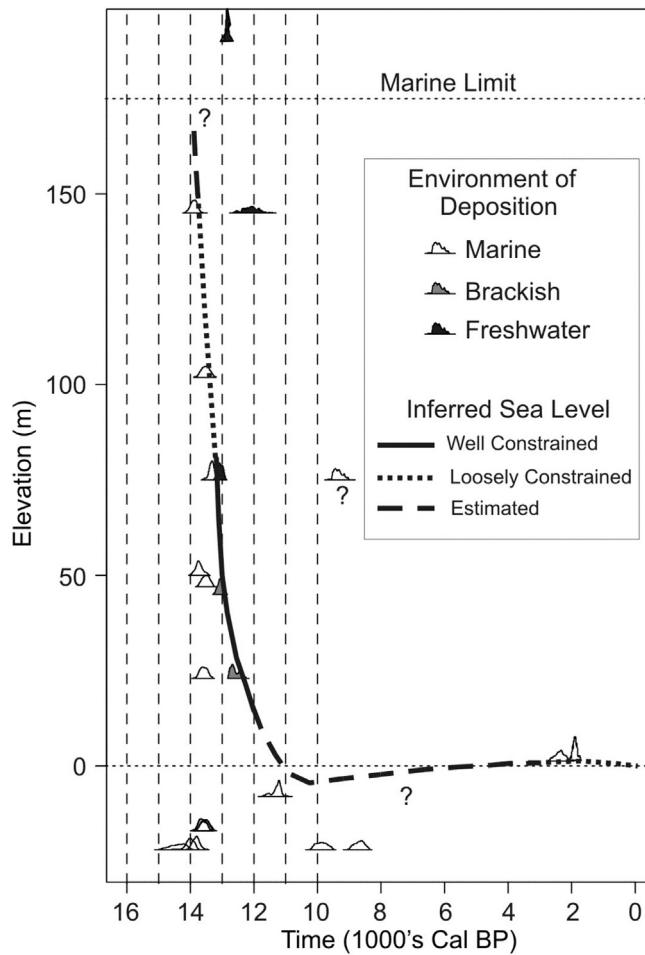
Samples were taken from ponds and bogs between elevations of

195 and 0.75 m ahht and from one lagoon with a sill 0.5–1.0 m bhht. Sampling was conducted from floating coring platforms in ponds and lagoons, or from the surfaces of bogs and marshes. Lake bottom sediments were sampled by driving the coring device into the substrate and retrieving the core by hand or with a portable winch. Elevations for each core site were measured relative to the sill of the sediment basin. Based on the local tidal range of 4–5.3 m in the study area (see Appendix 1 footnote), it is estimated that hht would have to be about 3 m or slightly more above sill height to produce fully marine conditions. For example, a sample with marine flora from a basin with a sill height of 173 m (above modern hht) would imply that the associated hht was at least 176 m above present-day higher high tide.

Cores were logged and sampled with specific attention to identifiable stratigraphic transitions. The transition from marine to terrestrial-derived sediment was commonly distinguished by marked changes in sediment character, such as from clastic sediments (e.g. clay, mud, sand, shell hash, gravel) to organic sediments (gyttja, peat) and confirmed by microfossil analyses. Diatom analysis and the presence of marine shells were the primary methods used for identifying salinity transitions (Fig. 4).

The presence of marine shellfish remains was useful in identifying marine sediment but differential preservation of shell in acidic pond environments limited their utility in identifying specific points of transition from marine to freshwater conditions.

Diatom species have known tolerances to water chemistry (e.g., salinity, acidity) and are generally well preserved in lake bottom sediments. These microflora are a good proxy for marine transgression and regression events (Zong and Sawai, 2015). All sediment cores were systematically sampled and slides for diatom analysis were prepared and examined following the method outlined by Battarbee (1986). Diatoms were concentrated by coarse sieving (500 µm), reserving the fine sediment and, where



**Fig. 3.** Previous sea level curve for the northern Strait of Georgia (James et al., 2005).

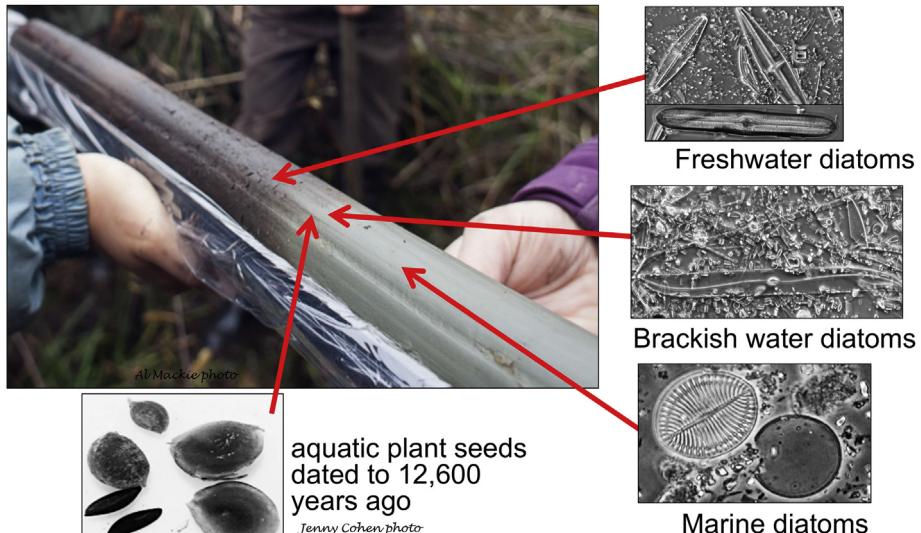
necessary, decanting the clay fraction. For two samples, BB136 and BB140, the clay fraction made it difficult to view diatoms and was removed using 10- $\mu\text{m}$  mesh, which would have removed smaller diatoms from the analysis. Samples were plated onto microscope

slides using Naphrax or Norland Optical Adhesive #61. Slides were analyzed using transmitting light microscopes to assess the presence of diagnostic diatoms at stratigraphic transitions. For most slides, a minimum of 250 diatoms was counted at 1000x magnification. In a few cases diatoms were rare and as few as 150 diatoms were counted (Supplementary Table S1).

Observed diatom floras were compared to those identified in Campeau et al. (1999), Cumming et al. (1995), Falu et al. (2000), Foged (1981), Hein (1990), Kelly et al. (2005), Pienitz et al. (2003) and Spaulding et al. (2010). Following Hustedt (1953), diatoms were assigned to five salinity classes: 1 - halophobian (fresh, salt intolerant), 2 - oligohalobous indifferent (freshwater), 3 - oligohalobous halophilous (freshwater species tolerant of salinity to 0.2 ppt), 4 - mesohalobous (brackish water species with optimal salinity between 0.2 and 30 ppt) and 5 - polyhalobous (marine water species with optimal salinity greater than 30 ppt). The salinity tolerance of identified floras was determined using the latter diatom flora references and data from Denys (1992), Guiry and Guiry (2017), Hustedt (1953), Marohasy and Abbot (2007), Wilson et al. (1996) and Zong and Sawai (2015). Chronological control was subsequently obtained by radiocarbon dating organic samples such as seeds and conifer needles where sediment characteristics or diatom analysis indicated a transition in the environment of deposition (Appendix 1).

## 2.2. Marine sediment sampling

In this study, we observed late glacial and early Holocene paleomarine deposits in the modern intertidal zone and at higher elevations inland associated with past shorelines (Fig. 5). These deposits were sampled from natural exposures as well as auger (7 cm diameter) and shovel tests. Microfossil (e.g., diatom) and macrofossil (e.g., shellfish, peat, etc.) analyses were conducted to identify sediment character. The position and age of paleomarine samples provides a lower limit for former high tide position. More precise limits can be determined from butter clams (*Saxidomus gigantea*) recovered in growth position. Since the tidal range of this species extends up to ~0.5 m above chart datum (Baxter, 1971; Quayle and Bourne, 1972) we can use this upper range to estimate the lowest possible RSL position by subtracting 0.5 m from the local tidal range (Appendix 1) and adding this value to the elevation of



**Fig. 4.** Plant macrofossil and diatom proxies, combined with visual and textural sediment characteristics, aid in identification of the transition from marine (grey marine clay) to fresh water sediment (brown gyttja) at Blockhouse Bog. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



**Fig. 5.** (a) 12,800 year-old marine mollusks exposed on the 6.6 m ahht shore of Village Bay Lake; (b) paleo-marine sediment exposed beneath clam garden wall at Kanish Bay.

the collected growth position sample. As with isolation basin cores, samples from these marine sediments were radiocarbon dated and the inferred minimum higher high tide position incorporated into the construction of the sea level history.

### 2.3. Archaeological sampling

Archaeological samples were obtained from exposed sections, auger and shovel tests and controlled excavations. Radiocarbon ages were obtained from samples collected from cultural deposits and, where present, from underlying marine sediment.

### 2.4. Radiocarbon dating

The RSL history presented here relates the radiocarbon ages of organic material to past sea levels between 1 m below and 197 m above the modern higher high tide mark. Organic samples were sent to the W.M. Keck AMS Laboratory in Irvine, California (UCIAMS) for Accelerator Mass Spectrometry (AMS) radiocarbon dating ([Appendix 1](#)). All radiocarbon ages reported here are calendar years ago (cal BP). Calibrations were undertaken using Calib 7.1 ([Reimer et al., 2013](#)) and are reported here as 2 sigma ranges. Marine shells younger than 10,000  $^{14}\text{C}$  BP were assigned a Delta R correction of  $320 \pm 90$  and samples older than 10,000  $^{14}\text{C}$  BP assigned a Delta R correction of  $550 \pm 50$  following [Hutchinson et al. \(2004b\)](#). These regional offsets, developed for the Strait of Georgia area ([Hutchinson et al., 2004b](#)) are in addition to the time-varying global marine reservoir correction built into Calib of about 400 years ([Reimer et al., 2013](#)). All dates discussed in the text are in calendar years (cal BP), while [Appendix 1](#) gives ages in both radiocarbon and calendar years.

## 3. Sea level investigation results

A total of 122 radiocarbon ages of organic material from known elevations constrain a revised sea level history for Quadra Island ([Appendix 1](#)). These include 66 ages from isolation basins, 24 from paleo-marine deposits and 32 from archaeological sites. Ninety-eight ages are new and 24 were previously reported by [James et al. \(2005\)](#) and [Tonello et al. \(2015, 2016\)](#). The highest sediment basin from which we retrieved a core containing a marine-freshwater transition had a sill height of 195 m ahht. Attempts to core basins at 200–205 m ahht were unsuccessful.

### 3.1. Isolation basins

Constraints from thirteen isolation basins, including six lakes, five bogs, a marsh and a lagoon, contribute to the refined sea-level curve. The following describes these, ranging from the highest to lowest elevations and includes three isolation basins described by [James et al. \(2005\)](#). A chart (based upon data in Supplemental Section - [Table S1](#)) presents a summary of microfossil analysis at the marine to fresh transition for some basins. Diagrams of relevant cores ([Figs. 6 and 7](#)) indicate sedimentary textures, paleoenvironments inferred from diatom and macrofossil analysis and radiocarbon ages. For each basin, the key result is the timing of the regression from, or transgression of, the constraining sill.

#### 3.1.1. Assu Bog (sill elevation 195 m above higher high tide (ahht))

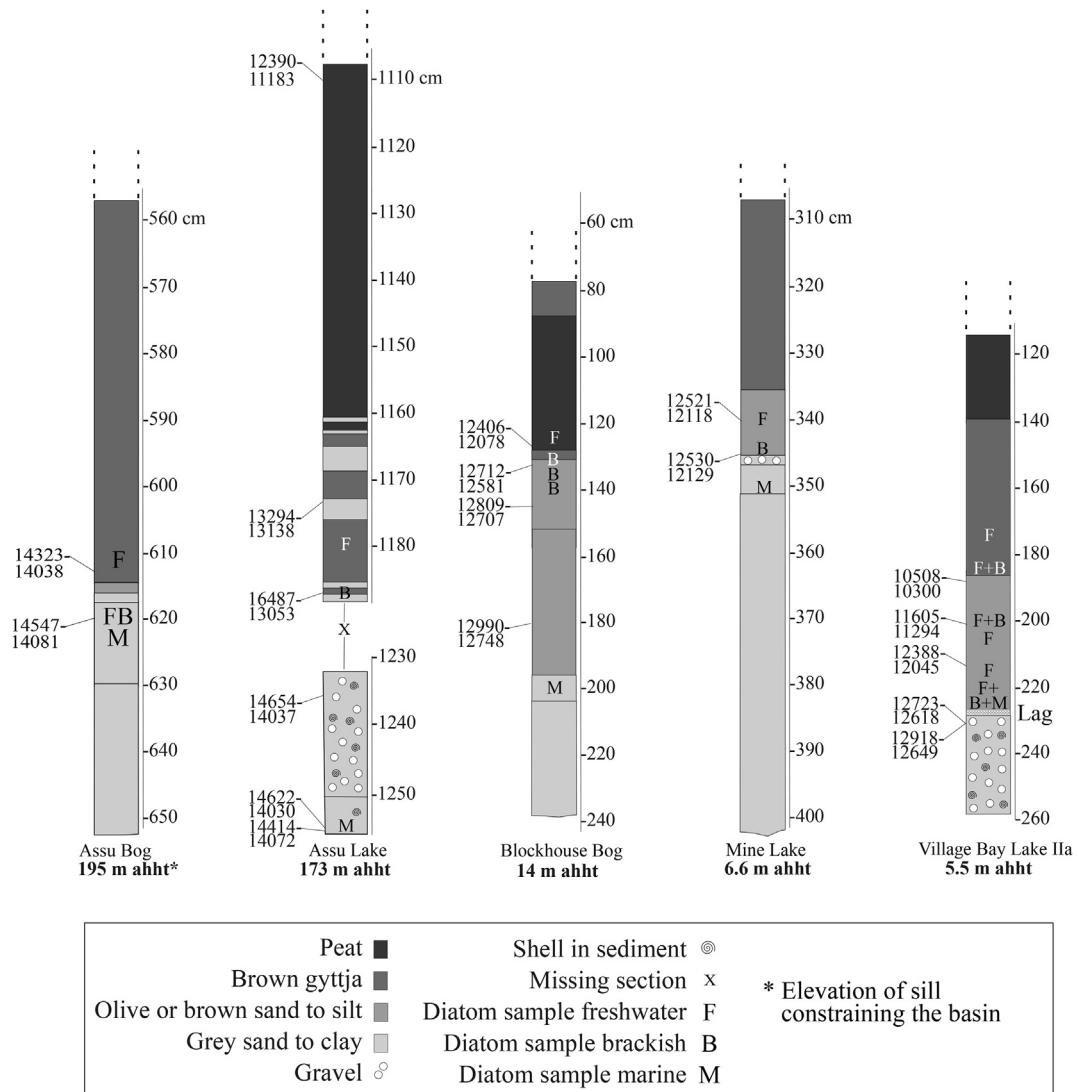
This core features grey clay-rich silt from 653 to 616 cm below sediment surface (bss) overlain, in turn, by brown gyttja to 140 cm, water and a (floating) 50 cm thick herb vegetated peat mat. The diatom assemblage indicates a shift from marine to freshwater conditions between 622 and 616 cm bss ([Figs. 6 and 8, Appendix 1](#)). Crowberry seeds from 621 to 614 cm respectively date to 14,547–14,081 (UCI, 191428) and 14,323–14,038 (UCI, 191429) years ago ([Appendix 1](#)). RSL was at least 197 m above present-day ca. 14,300 years ago and fell below 195 m before 14,200 years ago.

#### 3.1.2. Assu Lake (sill elevation 173 m ahht)

This core features basal shell-rich clastic deposits overlain by 1160 cm of brown gyttja. The diatom assemblage indicates a shift from brackish to freshwater conditions between 1188 and 1182 cm bss ([Figs. 6 and 9, Appendix 1](#)). A date on wood from 1188 cm has too large a standard error to be useful but three dates from near the base of the core range from 14,622–14,030 (UCI 169210) to 14,414–14,072 (UCI 169387) years ago. A pine bract associated with freshwater diatoms at 1173 cm dates to 13,294–13,138 (UCI 169386) years ago ([Appendix 1](#)). RSL was at least 175 m above present-day 14,300 years ago and fell below 173 m before 13,200 years ago.

#### 3.1.3. Beaver Lake (sill elevation 144m ahht)

A date of 14,170–13,627 (TO 9911) years ago was obtained for a *Mya truncata* (softshell clam) shellfish valve recovered at 870 cm depth ([Appendix 1](#); [James et al., 2005](#)). This species lives in lower intertidal and subtidal environments ([Coan et al., 2000](#); [Baxter,](#)



**Fig. 6.** Isolation basin core diagrams for Assu Lake, Blockhouse Bog, Mine Lake and Village Bay Lake showing nature of sediment, inferred paleoenvironment from diatom analysis (see Appendix 1 and Figs. 8–12) and two sigma calibrated radiocarbon age ranges (cal BP). Depths in cm are relative to the sediment surface (top of core). See James et al. (2005) for core diagrams for Beaver Lake, Whittington's Bog and Ballard's Bog.

1971) indicating that RSL was at least 147 m above modern at that time.

### 3.1.4. Morte Lake (sill elevation 90 ahht)

An exposure of marine sediment, characterized by abundant scallop shells, was observed in shallow water on the west side of the lake. The location was sampled by collection of shell and wood from the exposed clay and by auger testing to one metre depth below the sediment surface. Organic material included abundant *Patinopecten caurinus* (Weathervane scallop) shells, a few small *Saxidomus gigantea* (butter clam) and *Protothaca staminea* (little-neck) clams, *Euechinoidea* (sea urchin) and woody debris. The sediment was disturbed (likely by log booming operations about 100 years ago) as the shell dates ranged from 14,084–13,746 (UCI 146060) to 13,877–13,504 (UCI 146055) years ago (Appendix 1) while the wood dates were modern. *P. caurinus* is a subtidal species inhabiting moderate to high-energy marine environments at depths below 10 m (Coan et al., 2000). Sea level was therefore at least 100 m above modern ca. 13,700 years ago.

### 3.1.5. Whittington Bog (sill elevation 75m ahht)

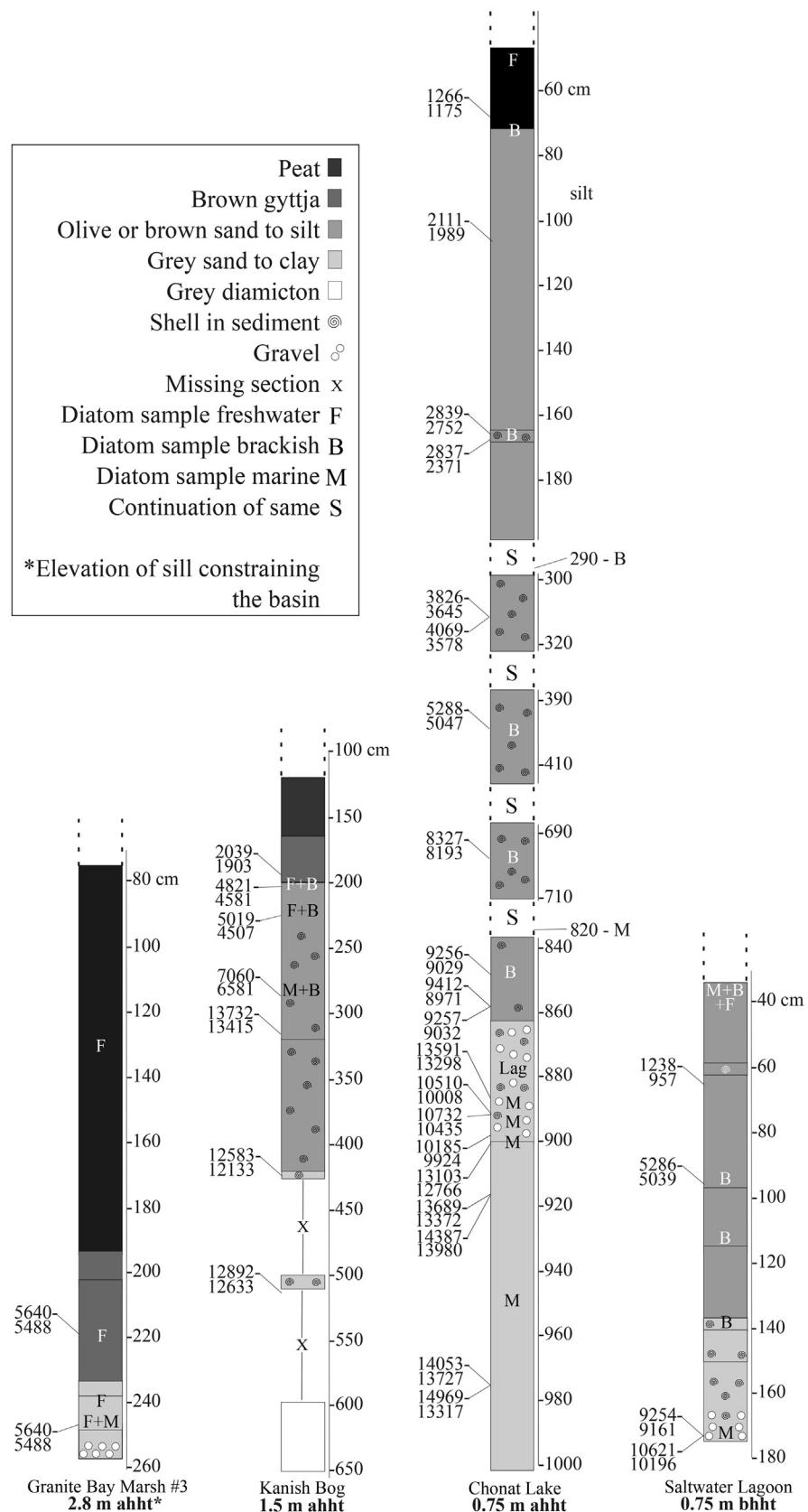
Coarse basal sand containing wood dated to ca. 13,475–13,130 (TO 10817) years ago was interpreted to be marine (James et al., 2005).

### 3.1.6. Ballard's Bog (sill elevation 26 m ahht)

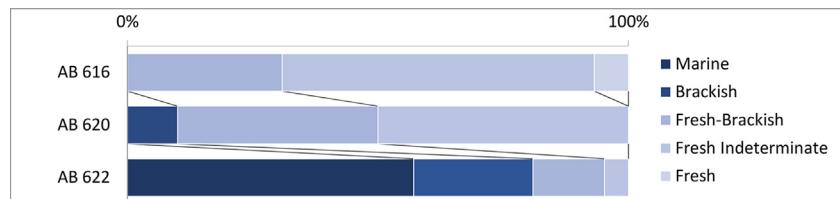
Brackish and freshwater diatoms from a sediment core are associated with a date of 12,704–12,403 (TO 9914) years ago (Appendix 1) (James et al., 2005). These data suggest the basin became freshwater around this time. A shell from a blue-grey clay layer in a nearby excavated pond dates to ca. 13,600 (TO 9896) years ago (Appendix 1). The identification of the shell as a Mask Limpet (*Tectura persona*), an intertidal species, may be in error as RSL is interpreted to be much higher at this time.

### 3.1.7. Blockhouse Bog (sill elevation 14.2 m ahht)

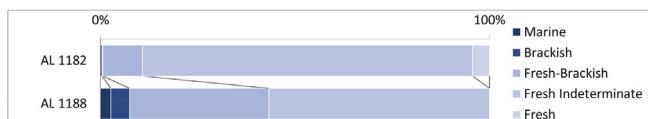
The core features basal grey clay-rich silt deposits from 238 to 130 cm, overlain by a thin layer of brown gyttja and peat. The diatom assemblage indicates a shift from brackish to freshwater conditions at 133 cm (Figs. 6 and 10, Appendix 1). Freshwater plant



**Fig. 7.** Isolation basin core diagrams for Granite Bay Marsh, Kanish Bog, Chonat Lake and Saltwater Lagoon, showing nature of sediment, inferred paleoenvironment from diatom analysis (see Appendix 1 and Fig. 13–16) and two sigma calibrated radiocarbon age ranges (cal BP).



**Fig. 8.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages at Assu Bog (Table S1; AB) showing transition from marine basin to freshwater pond.



**Fig. 9.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Assu Lake (AL) showing transition from brackish lagoon to freshwater pond by 1182 cm bss.

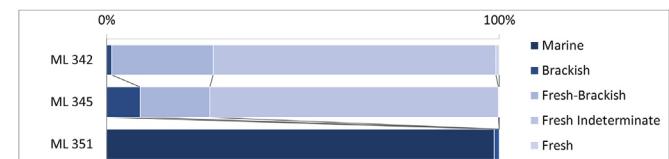
seeds (*Potamogeton* sp.), associated with mixed fresh and brackish water diatoms from that depth, were dated to 12,712–12,581 (UCI 134825) years ago (Appendix 1). These data indicate RSL fell below 14 m elevation by that time.

### 3.1.8. Mine Lake (sill elevation 6.6 m ahht)

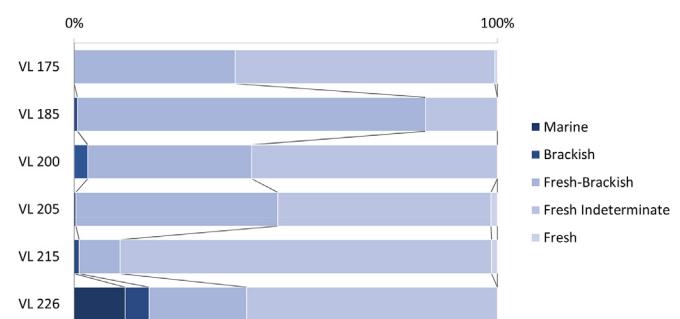
The core features grey clay-rich silt from 410 to 346 cm below sediment surface, overlain by coarse sand, possibly representing an erosional lag and 346 cm of tan-grey and medium brown gyttja. Diatom analysis of samples from the Mine Lake core identified a shift from mixed freshwater and lagoonal species at ca. 12,530–12,129 (UCI 134823) years ago to fresh water by 12,521–12,118 (UCI 134822) years ago (Figs. 6 and 11, Appendix 1). No organic material suitable for dating was recovered from the underlying marine sediment. These data indicate RSL fell below 6.6 m elevation about 12,350 years ago.

### 3.1.9. Village Bay Lake (sill elevation 5.5 m ahht)

The core features basal shelly sands and gravels (250–230 cm bss) overlain by an organic-rich light brown silt (230–185 cm) and capped by dark brown gyttja and decomposed peat. Diatom analysis of samples from the Village Bay Lake core identified a rapid transition from marine conditions at 12,918–12,649 (UCI 175372) to 12,723–12,618 (UCI 175367) years ago to brackish and then fresh conditions by 12,388–12,045 (UCI 186380) years ago (Figs. 6 and 12, Appendix 1). The presence of halophobian (salt intolerant) species at 205–215 cm indicates that a fully freshwater environment had developed by ca. 12,200 years ago. The occurrence of some brackish diatoms and abundant fresh-brackish types in these same levels suggests fluctuating RSL with higher high tide close to the sill elevation or, some mixing (e.g., bioturbation) with overlying brackish sediment. At 11,605–11,294 (UCI 175366) years ago the



**Fig. 11.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Mine Lake (ML) showing transition from marine basin at 351 cm bss to brackish lagoon by 345 cm and freshwater pond at 342 cm.

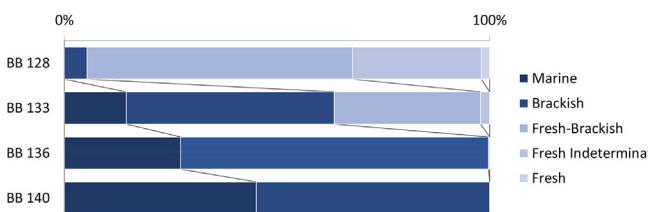


**Fig. 12.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Village Bay Lake (VL) showing transition from marine-brackish basin to fresh-brackish by 215 cm bss, to a freshwater pond by 175 cm.

diatom flora is largely freshwater but includes a significant percentage of fresh-brackish species (Fragilaria-type – e.g. *Pseudostaurosira*, *Staurosirella*) and no halophobian species. High percentages of Fragilaria-type diatoms are often coincident with salinity and water chemistry changes at the point of basin isolation (Miettinen et al., 2007; Mills et al., 2009). Taken together, these data may reflect a high tide position a few metres below the Village Bay Lake sill ca. 11,400 years ago. A sea level position 3 m–4 m above modern could result in salinity fluctuations resulting from occasional storm surge marine incursions and salt spray from the adjacent exposed rocky shoreline. Alternatively, the fresh-brackish dominated diatom assemblages could reflect a decrease in lake acidity in association with climatic change (cf. Rosen et al., 2001; Ruhland et al., 2015). The basin was fully fresh by 10,508–10,300 (UCI, 184908) years ago (Appendix 1, Fig. 12).

### 3.1.10. Granite Bay Marsh (sill elevation 2.8 m ahht)

The core features basal sands and gravels (255–245 cm bss) overlain by peaty gyttja (230–190 cm) and dark brown peat (190–0 cm). Sediment from the peat layer to 240 cm depth is strongly dominated by freshwater diatoms. A mix of fresh and marine diatoms from 248 cm suggests that the basal sediment reflects a freshwater pond environment subject to occasional marine washes (Figs. 7 and 13, Appendix 1). The date of 5640–5488 (UCI 139559) years ago from 220 cm implies that the basin was freshwater and sea level below 2.8 m elevation by that time (Appendix 1). An identical date from 249 cm (UCI 139560) raises the



**Fig. 10.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Blockhouse Bog (BB) showing transition from brackish lagoon at 133 cm bss to freshwater bog at 128 cm bss.

possibility that the dated spruce needle at 249 cm may have been dragged down from the gyttja layer by the corer. The transition from marine to freshwater conditions occurred earlier than ca. 5500 years ago.

### 3.1.11. Kanish Bog (sill elevation 1.5 m ahht)

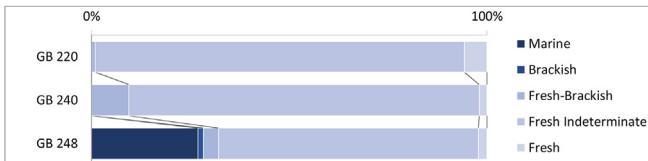
A 6.5 m core revealed peat overlying clastic sediments with diatoms indicating phases of marine, lagoonal and freshwater sedimentation (Appendix 1, Figs. 7 and 14). Radiocarbon ages of marine shell and wood associated with marine diatoms suggests the basin was fully marine at 13,732–13,415 (UCI 172676) years ago, lagoonal (high tide mark between 5 m and 2 m above modern) from ca. 7060–6581 (UCI 172675) to at least 4821–4581 (UCI 172668) years ago and freshwater from 2039–1903 (UCI 172667) years ago to present (Fig. 15, Appendix 1, 2). The chronological hiatus from ca. 12,400 to 6800 years ago may reflect tidal winnowing while sea-level stood slightly higher than 1.5 m ahht.

### 3.1.12. Chonat Lake (sill elevation 0.75 m ahht)

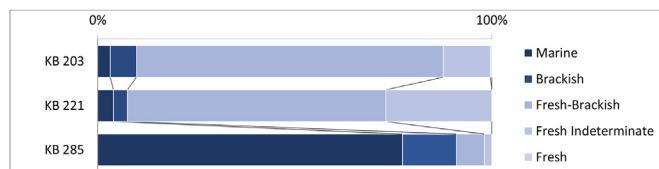
A 400-cm long Bolivia and a 1000-cm long Livingstone core were recovered a few metres apart. The composite core features a grey sandy shelly silt (1010–900 cm), overlain by a subangular shelly gravel (900–860 cm), interpreted as a lag deposit and overlain, in turn, by shell-hash-rich sandy silt, fining upwards to silt (860–400 cm). Above this lies olive-brown shelly silt (400–170 cm) and brown silt (170–70 cm), capped by olive brown gyttja (70–0 cm). Diatom analysis indicates that the basal sediments (860 cm to base of core) are marine, while the overlying silts are lagoonal, deposited in a low-energy environment. Within the interpreted lag deposit, a date of 10,185–9924 (UCI 169384) years ago on wood and dates of 10,510–10,008 (UCI, 186286), 10,732–10,435 (UCI, 186287), 13,103–12,755 (UCI 169208) and 13,591–13,298 (UCI 172679) years ago on shell were all recovered between 889 and 895 cm core depth. It is likely that this sediment unit includes intertidal to shallow subtidal material carried over the basin sill when it was in the wave active zone. This would imply sea levels one to four metres above modern at the time of deposition. AMS dating of marine shell and wood associated with proxy diatoms suggests the basin was fully marine from ca. 14,100 to 13,000 years ago. Samples from the inferred lag layer (900–870 bss) are dominated by marine diatoms but include some brackish diatoms (Figs. 7 and 15). This may reflect a shift from marine to marine-brackish conditions at some point within this ca. 13,000 to 10,000 years ago interval. The basin was a brackish lagoon (high tide mark between 3 m and 1 m above modern) from 9256–9029 (UCI 163220) to 2111–1989 (UCI 139563) years ago and freshwater by 1266–1175 (UCI 139562) years ago (Appendix 1).

### 3.1.13. Saltwater Lagoon (sill elevation 0.75 bhht)

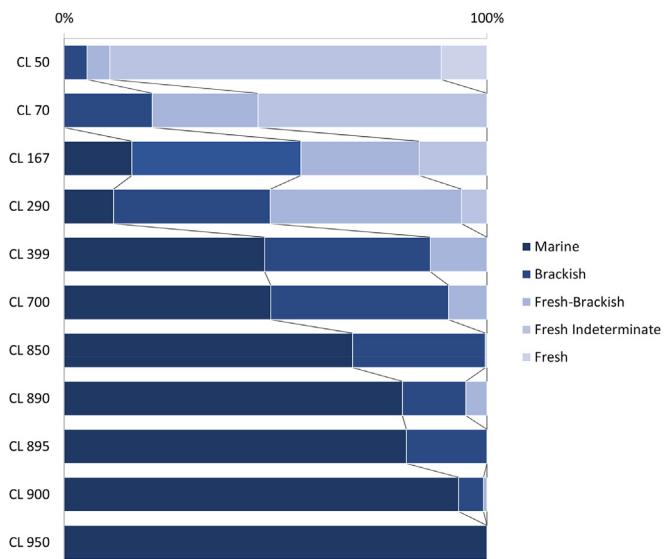
The core features shelly gravel (175–165 cm) overlain by shelly sands and silts (165–140 cm) and olive grey silt (115–0 cm) (Fig. 7). AMS dating of marine shell associated with a marine-brackish diatom assemblage indicates high tide was at least two metres



**Fig. 13.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Granite Bay Marsh (GB) showing transition from freshwater pond with marine incursions at 248 cm bss to a freshwater pond by 240 cm.



**Fig. 14.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Kanish Bog (KB) showing transition from marine-brackish lagoon to a slightly brackish pond by 221 cm bss.

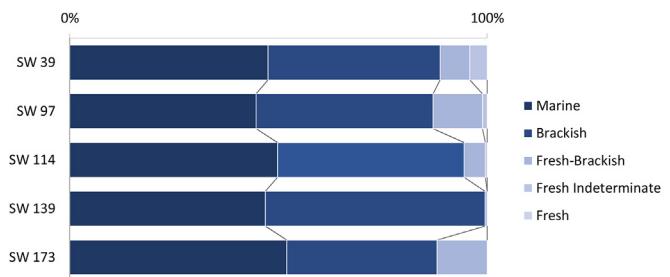


**Fig. 15.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Chonat Lake (CL) showing transition from marine basin to a marine-brackish lagoon, to a progressively less saline lagoon and to a freshwater pond.

above the sill of the lagoon 10,621–10,196 (UCI 134624) to 9254–9161 (UCI 134820) years ago (Appendix 1). Diatom analysis and dating suggest that the shoreline was at or above present-day hht from that time until at least 1283–957 (UCI 134818) years ago (Figs. 7 and 16; Appendix 1).

### 3.2. Marine sediment exposures

We investigated nine early post-glacial marine exposures in the Quadra Island area. These include a marine section on Saxon Pond Creek, five areas of raised marine deposits in the Village Bay to Yeatman Bay area and three locations in Kanish Bay.



**Fig. 16.** Percentages of diatom halobian classes as proxies for salinity from diatom assemblages (Table S1) at Saltwater Lagoon (SW) indicating salinity changes from a marine dominated basin at 10,400 years to a brackish lagoon.

### 3.2.1. Central Quadra

Saxon Pond Creek on central Quadra Island was previously investigated by James et al. (2005). A *Clinocardium nuttallii* (cockle) shell collected from a creek bank exposure of marine sediment, at 50 m ahht, was dated to 13,497–13,098 (TO 10817) years ago (Appendix 1). This is a lower intertidal to subtidal species (Coan et al., 2000) indicating RSL was at least 53 m above modern at that time.

### 3.2.2. Village Bay to Yeatman Bay

Paleomarine sediments containing clam shells at Village Bay Lake and Mine Lake are both 6.5 m above modern high tide (ca. 10 cm below summer low water lake-level). Butter clams, in growth position, and wood from exposed paleo-marine sediment at Village Bay Lake were dated from 12,905–12,688 (UCI 155090) to 12,894–12,614 (UCI 155102) years ago (Fig. 5, Appendix 1). Butter clams, in growth position, and wood from exposed paleo-marine sediment at Mine Lake were dated to 12,871–12,609 (UCI 146064) and 13,049–12,780 (UCI 146063) years ago respectively (Appendix 1). Shellfish from these exposures include marine species such as *Balanus nubilus* (giant acorn barnacle), *Saxidomus gigantea* (butter clam) and *Protothaca staminea* (little-neck clam) that inhabit both lower intertidal and subtidal environments (Baxter, 1971). This indicates that the commensurate high tide mark was at least 3 m higher than the modern elevation of this lake system and therefore more than 9.5 m above modern at the time of deposition.

At three archaeological sites, casts of marine mollusks as well as brackish and marine diatoms were recovered from silt and fine sand sediment underlying archaeological deposits. These appear to be deltaic sediments. At sites EbSh-81 (10–12 m ahht) and EbSh-98 (11–13 m ahht) these sediments contain charcoal fragments dating to ca. 12,700 years ago (Appendix 1; Lausanne, 2018). At site EaSh-81 (26–30 m ahht) the deltaic deposits are suggested to date to ca. 12,900 based on local sea level history (Fig. 19 below).

### 3.2.3. Kanish Bay area

In Kanish Bay, early Holocene butter clam assemblages have been identified below three archaeological ‘clam garden’ sites (Toniello et al., 2015, 2016). While the archaeological features date to the late Holocene (Lepofsky et al., 2015), paleomarine sediments are preserved below them and contain butter clams in growth position ranging in age from 11,280–11,028 (UCI 171655) to 10,089–9531 (UCI 163685) years ago (Appendix 1). The elevations of recovered growth position shellfish range between 0.4 m and 1.6 m above Chart Datum (CD) today and are found in two distinct stratigraphic units (Fig. 18) implying early Holocene sea level positions at least 0.0 and 1.1 m above modern hht (Appendix 1). These represent the lowest possible shoreline elevations during this interval as subsidence and auto-compaction (Massey et al., 2006) likely lowered the intertidal sediment during the Holocene (cf. Crowell, 2017; Hodgson, 1946; Rogers, 1980; see also discussion in section 4.2 below).

A distinct stratigraphic layer consisting of a grey-blue sandy, paleomarine clay containing small butter clams dating from 11,280–11,028 (UCI 171655) to 11,084–10,719 (UCI 159608) years ago was found at both the Double Wall (EbSh-5) and the High and Dry (EbSh-36) sites (Toniello et al., 2015, 2016). At High and Dry, the preservation of barnacle scars, dating to ca. 11,000 years ago (UCI 159609, 159610), on a former beach surface suggests rapid burial of the barnacle scarred rocks (Kowalewski et al., 2017; Lepofsky et al., 2015). Above this paleomarine deposit is a life-position shell bed measuring 60 cm thick with several stratigraphically consistent dates on paired butterclam valves ranging from 10,827–10,501 (UCI 159607) to 10,651–10,218 (UCI 171657) years ago (Fig. 17, Appendix

1). The profile at High and Dry suggests rapid subsidence or cessation of sea level fall ca. 11,000 years ago, followed by rapid sedimentation within the next 500 years as the shoreline recovered to its natural slope.

### 3.3. Data points from archaeological sites

Thirty-two radiocarbon ages, from basal strata at eleven archaeological sites, help constrain the sea level record (Appendix 1). Samples dated from archaeological components are assumed to have been above higher high tide at the time of deposition. Four data points are from shell middens adjacent to the modern ocean shore and twenty-eight are from sites on raised marine landforms such as paleo-deltas and beaches. Ages from the archaeological samples help to constrain the Holocene portion of the sea level curve post-dating 11,000 years ago. The oldest radiocarbon dated archaeological component is at Yeatman Bay on northeast Quadra Island where several dates between 11,127–10,786 (UCI, 193679) and 10,516–10,254 (UCI, 193680) years ago were obtained from a paleosol at 3.5 m ahht (Appendix 1). The archaeological sediments contained abundant stone tools and charcoal as well as a combination of terrestrial protists and nearshore benthic diatoms (likely washed onto a supratidal berm by wave action during extreme tides). All of the more recent archaeological dates (Appendix 1) appear to be associated with terrestrial sediment above the supratidal zone.

### 3.4. Developing the sea-level history

The local relative sea-level history, relative to modern high tide, was refined by cross-referencing data from sample sill elevations, radiocarbon ages (Appendix 1) and proxy indicators of sea level position (terrestrial, intertidal, marine) (Table S1). Sea level constraints from isolation basin analyses provide the outline of shoreline change (Fig. 18), especially during late glacial and early deglacial times when sea-level fell rapidly from its highstand position. Data from paleo-marine sections and archaeological sites further refine the history (Fig. 19), especially from about 12,000 years ago to the present. The maximum RSL position is not known for certain but LiDAR images of apparent beach ridges (Figs. 20 and 23) at Elk Bay (4 km west of Kanish Bay on northwest Quadra) extend to ca. 205 m ahht and may indicate the approximate marine limit.

RSL fell from a high-stand at or above 197 m above modern levels at 14,300 years ago to 6 m by 12,300 years ago. Sea level appears to have fallen to ca. 2–4 m elevation shortly after 12,300 years ago. Village Bay Lake (ca. 5.5 m sill elevation) was fresh between ca. 12,300 and 11,400 years ago while Chonat Lake (ca. 1 m sill elevation) was marine to brackish-marine at that time. A possible minor marine transgression to ca. 4 m above modern about 11,400 years ago is suggested from the Village Bay Lake diatom record. At ca. 10,980 to 10,400 years ago a RSL position ca. 3 m above modern is indicated from data obtained at the Yeatman Bay archaeological site. This is consistent with the growth position butter clam data from Kanish Bay that imply a RSL position above modern levels ca. 11,200 to 10,000 years ago. After this time sea levels appear to have fallen slowly to the current elevation (0 m ahht).

Stillstands or slowstands may have occurred during relative sea-level fall. A series of broadly distributed raised marine terraces have been identified from preliminary observations in the field, archaeological investigations and initial examination of LiDAR imagery (Fedje et al., 2016; Lausanne et al., 2017; Lausanne, 2018).

A marine terrace at ca. 26–30 m is less prominent than lower terraces but discernible from LiDAR mapping in both north and

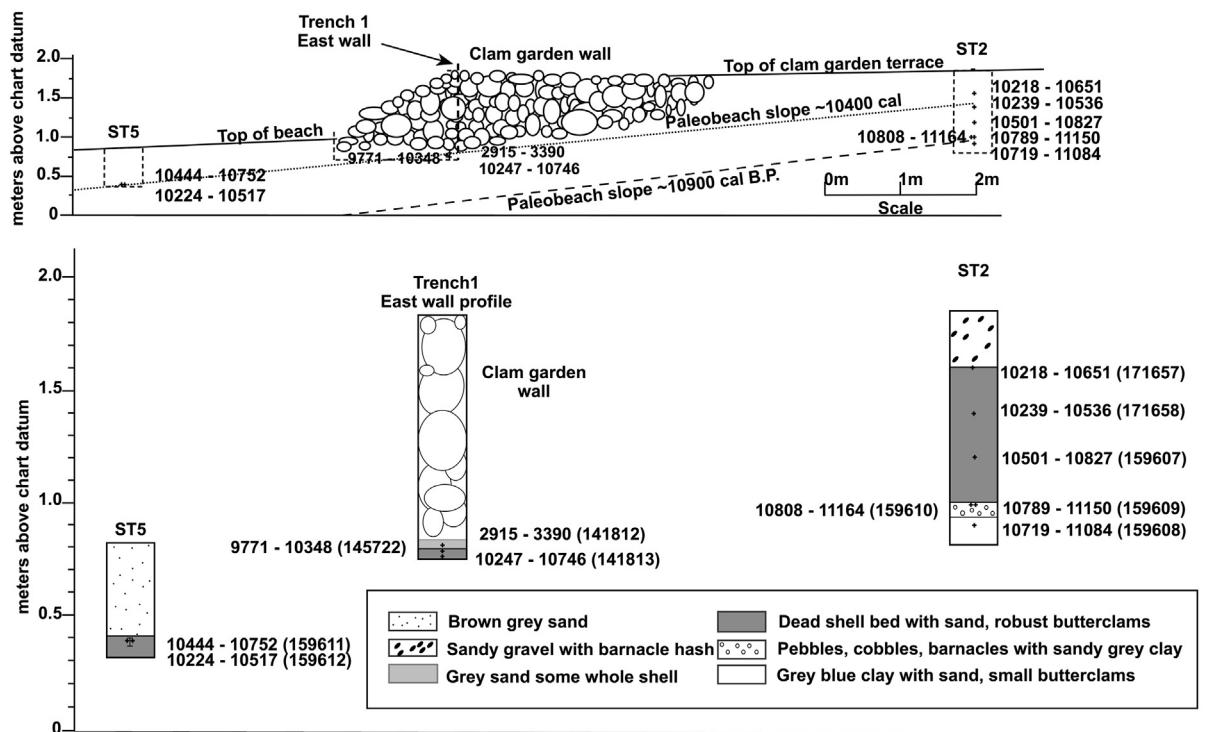


Fig. 17. Stratigraphic profiles and radiocarbon dates from High and Dry (EbSh-36) (Tonello et al., 2015, 2016).

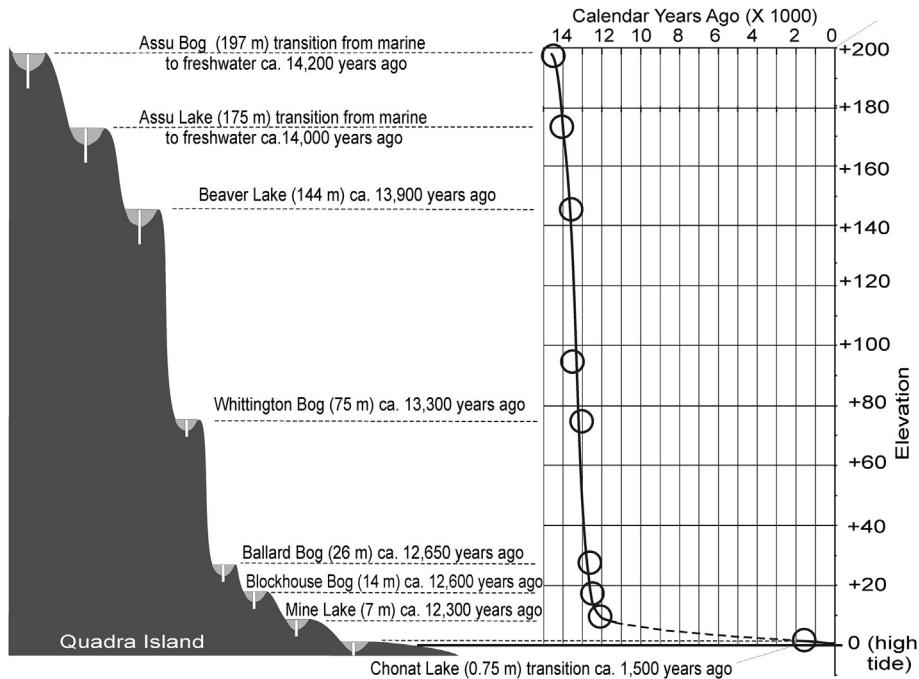


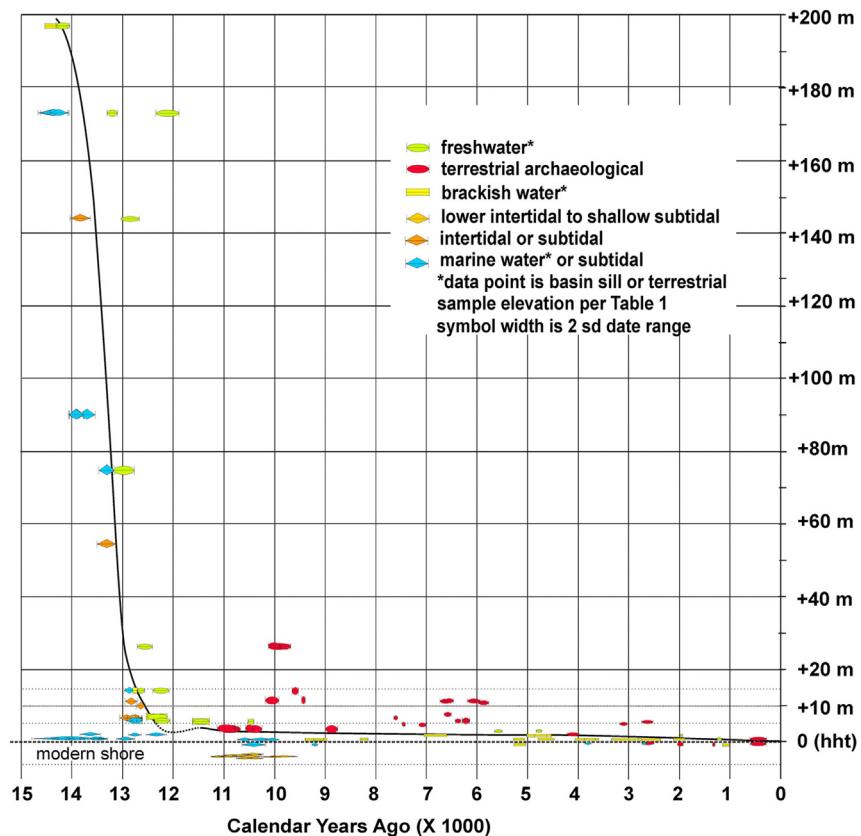
Fig. 18. Cores from isolation basins provide the constraints to develop a preliminary sea-level history.

south Quadra Island (Lausanne, 2018). This terrace exhibits a break-in-slope at ca. 26 m ahht (paleo-lower low tide mark) and low-slope 'paleo-intertidal' zone extending to ca. 30 m ahht. An example of this landform includes a wave cut terrace at the Lactarius Road site on Village Bay (Fig. 21a) and dates to ca. 13,000 years ago based on the Quadra sea-level curve.

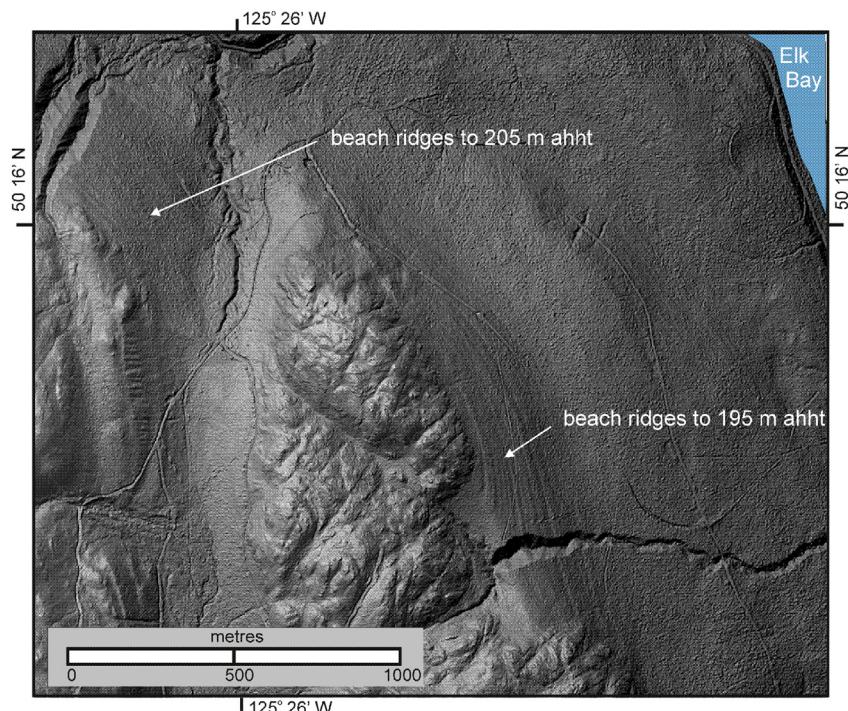
A ca. 10–14 m ahht terrace and associated break in slope is well

developed along many sections of sediment-dominated shoreline (Lausanne, 2018) and may represent a 'paleo-intertidal' zone. The Crescent Channel (Fig. 21b) and Yeatman Bay (upper component) archaeological sites are associated with this landform. Charcoal fragments from deltaic sediments at these sites were dated ca. 12,700 years ago (Appendix 1).

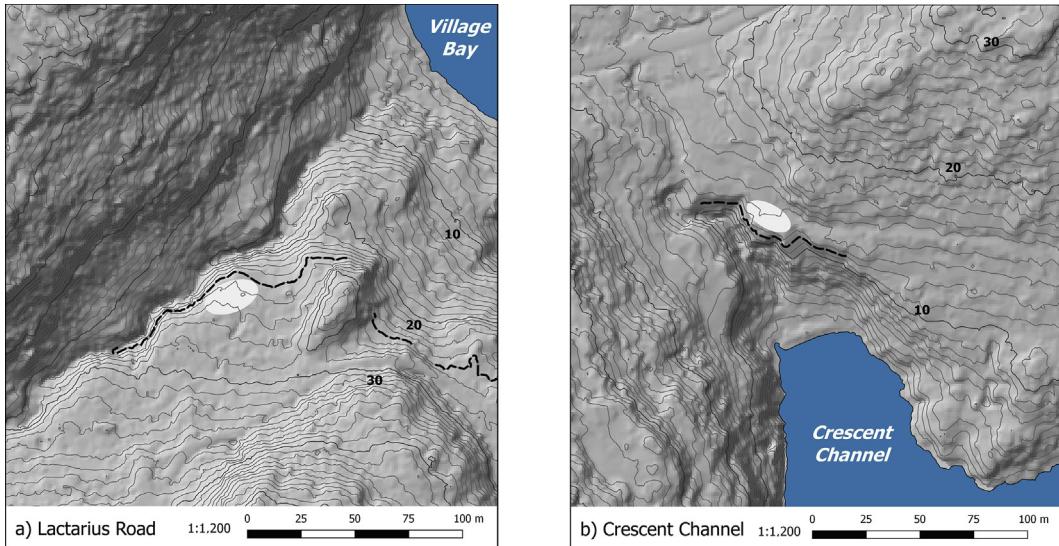
A lower elevation marine terrace, between 3 and 5 m ahht, has



**Fig. 19.** Final refined sea level curve for the northern Strait of Georgia, based on data from Quadra and Read Islands. A low-amplitude transgression around 12,000 to 11,400 year ago is inferred from the information presented here.



**Fig. 20.** LiDAR bare earth model of apparent beach ridges, to ca. 205 m ahht, near Elk Bay on the east coast of Vancouver Island. This site is approximately 4 km west of Kanish Bay on Quadra Island. Bare earth image provided by Bruce Gullickson, Interfor Corporation.



**Fig. 21.** Raised marine terraces at 26–30 m ahht at the Lactarius Road site (EaSh-81) on Village Bay (a) and 10–14 m ahht at the Crescent Road site (EbSh-81) on Crescent Channel (b). Bold dashed line is break-in-slope (front edge) of raised marine terrace. Light grey ellipses are raised beach archaeological sites. Digital elevation model and images prepared by C. Vogelaar and A. Lausanne.

been observed at a number of locations but is often difficult to resolve from LiDAR mapping due to the abundance of anthropogenic terraces (e.g., shell middens) below ca. 5 m elevation. The basal component of shell-free archaeological site EbSh-98, at 3.4 m ahht in a beach berm at Yeatman Bay, dates from before 10,980 to ca. 10,400 years ago (Appendix 1).

The berm sediments on the 3–4 m terrace and “paleo-intertidal” deposition at upper terraces between 10–14 m and 26–30 m imply a slowing or pause in marine regression of sufficient duration for the formation of these features.

#### 4. Discussion

##### 4.1. Revision of sea-level history

The new constraints and data reported here refine and revise the sea level history for the northern Strait of Georgia (James et al., 2005). Key revisions to the sea-level curve include: 1) isolation basin results from Assu Bog show that sea-level was above 197 m at 14,300 years ago, placing a minimum age constraint on the early post-glacial high-stand; 2) instead of the previously inferred, tentative shallow lowstand (<8 m bhht) in the early Holocene (James et al., 2005), diatom analysis and radiocarbon age constraints from the Chonat Lake cores suggests that sea-level fell to about 2–3 m above modern levels ca. 12,000 years ago and a lowstand below modern likely did not form; 3) detailed analysis of the Village Bay Lake core suggests a possible minor transgression ca. 12,000 to 11,400 years ago; and 4) over the last 10 millennia RSL fell slowly from ca. three metres to its present level.

We cannot rule out the possibility that sea-level briefly dropped below the sill elevation of Chonat Lake (0.75 m ahht) in the late Pleistocene, giving an ephemeral lowstand around 12,000 years ago, but consider it unlikely. There is an approximately 2300-year chronological gap in the lag deposit (ca. 12,900 to 10,660 years ago) in the Chonat Lake core and it is possible that evidence of a fresh-water phase has been removed through wave action. We note, however, that elsewhere in coastal British Columbia where freshwater basins are transgressed by a rising sea level, that the freshwater sediments (gyttja, peat) are preserved, such as on Lasqueti Island (Johnson et al., 2004), Victoria (Portage Inlet, James

et al., 2009a), Sooke (Anderson Cove, James et al., 2009a) and Hakai Passage (McLaren et al., 2014). Other evidence that sea-level was maintained slightly above present-day levels (0.5–1.5 m ahht) include growth-position clam beds dating from ca. 11,200 to 10,000 years ago at Kanish Bay, an archaeological site associated with a 3–4 m beach berm and, finally, a brief return to weakly brackish conditions at Village Bay Lake (5.5 m ahht) about 11,400 years ago. In any event, if sea-level did drop below the level of Chonat Lake sill, the regression was relatively brief and probably lasted no more than a few hundred years.

Similarly, the inferred 1–2 m sea-level transgression, based on the Village Bay Lake core, is tentative. It is possible that the observed freshening (accompanied by a small percentage of brackish diatoms), which suggests sea-level fall, followed by return to weakly brackish conditions suggesting a transgression, is due to other factors. For example, increased storminess, with sea level a few metres below the basin sill, could have introduced marine water through storm surges and ocean spray, or erosion may have delivered sediments having an intertidal provenance with accompanying brackish diatoms into the basin. When storminess decreased, or sea level fell further, delivery of marine waters to the basin would have stopped and a return to fully fresh conditions would be inferred. Alternatively, a dry climatic interval could result in lowered basin acidity and a consequent increase in fresh-brackish diatoms and absence of halophobic species. In these scenarios, the inferred paleoenvironment is a consequence of changes to climate and not to sea-level. In practice, both effects could be active.

##### 4.2. Disconformities

Sediment disconformities, including coarse-grained deposits and gaps in the chronological record, are seen in many of the isolation basins. Pronounced intervals of coarse-grained sediments (or alternatively gaps in the deposition of fine-grained sediments), interpreted as lag deposits, and gaps in the radiocarbon-based chronology were observed at Assu Lake (ca. 14,300 to 13,500 years ago), Mine Lake (ca. 12,370 years ago), Village Bay Lake (base of core to ca. 12,600 years ago), Kanish Bog (13,000 to 6500 years ago), Chonat Lake (ca. 13,500 to 10,000 years ago) and Saltwater

Lagoon (base of core to ca. 10,400 years ago). These disconformities may be the result of RSL regressing to the point where the formerly deep-water marine basins became subject to the effects of wave action when sea level fell to within a few metres of sill elevation (Fig. 22). During this time wave action could have removed some or all of the fine sediments. In addition, coarse sediments could have been transported from the ocean side of the basin sill by wave action. With further lowering of RSL to near sill elevation, the basins would have become protected lagoons as the sills dissipated wave energy. Fine sediment would again build up during this relatively quiescent marine phase as well as during the subsequent lacustrine history.

In contrast, cores from Beaver Lake (145 m), Whittington Bog (75 m), Ballard's Bog (23 m) and Blockhouse Bog (14 m) do not show a pronounced lag deposit at the transition from marine to freshwater conditions. This may reflect rapid sea-level fall, if the basin spent less time in wave-dominated depths and winnowing of fine sediments was restricted. Similarly, on southern Vancouver Island, James et al. (2009a) interpreted a sandy layer at the transition from marine to brackish conditions at Matheson Lake to reflect a high-energy environment that may reflect the slowing of the rate of sea-level fall. Higher-elevation sites in the same study, which experienced faster rates of sea-level fall, do not feature coarse sediment at the marine-freshwater transition (James et al., 2009a, Fig. 3). Thus, the pronounced presence of coarse sediments at the marine to brackish transition, interpreted as a lag deposit, and accompanying chronological gaps, may reflect a slower rate of sea-level change (a 'slowstand'). In this interpretation, the more massive and coarse lags at Assu Lake, Kanish Bog and Chonat Lake might reflect the longest slowstands.

#### 4.3. Geologic actors affecting interpretation of sea level history

Earthquake-induced subsidence events (slumping) have affected some locations within the Discovery Islands (Hodgson, 1946). It is likely such events also occurred in prehistoric time (cf. Mathewes and Clague, 1994). In addition, slow compaction and consolidation of sediments (Massey et al., 2006) may have lowered the surface of some organic and clay-rich beaches. Finally, tectonically-induced vertical crustal motion has been documented on crustal faults in Puget Sound (e.g., Johnson et al., 2004) and Victoria (Morell et al., 2017). Similar crustal faults may be active in the Discovery Islands region, although they have not yet been documented.

A number of subsidence and other tectonic-related events affected the northern Strait of Georgia at the time of the AD 1946 earthquake (7.1 magnitude) centred 25 km south of Quadra Island (Hodgson, 1946; Rogers, 1980; Rogers and Hasegawa, 1978). The events included tsunamis, liquefaction, terrestrial downdrops of up to 9 m (on Read Island), marine downdrops of up to 30 m (at Deep Bay) and beaches and spits 'disappearing', as well as terrestrial and

marine slumpages. Intertidal geysers of sand and clay-rich water were associated with some of the downdrop events.

These factors may complicate the interpretation of some constraining data. In the Quadra area, discordance in RSL position between coeval bedrock-constrained features and those on clay and organic-rich sediment may reflect compaction or prehistoric slumping. For example, data from Chonat Lake on north Quadra shows that sea levels were one metre or more above modern prior to 1000 years ago whereas at Waiatt Bay (EbSh-87 and EbSh-23), three kilometres to the south, terrestrially deposited midden dating from 2000 to 1500 years ago extends to more than one metre below the modern high tide mark (Crowell, 2017). Also, at several clam gardens in the region, we observed that the walls, which are thought to be constructed to a specific tidal height (Crowell, 2017; Deur et al., 2015; Groesbeck et al., 2014; Lepofsky et al., 2015), are up to one metre lower in elevation where not bedrock constrained (Crowell, 2017; Fedje et al., 2016). The 'lowered' (e.g. dipping clam garden walls and intertidal midden strata) features are located in areas with organic and clay-rich underlying sediments.

Paleobeaches at Kanish Bay (immediately west of Waiatt Bay - Fig. 1) dating between ca. 11,200 and 9000 years ago (see Section 3.2) suggest a sea level position ca. 2 m below that determined from isolation basin data at nearby Chonat Lake. Analysis of LiDAR imagery has identified a series of paleobeaches at a consistent elevation of 26 m aht between Kanish Bay and Village Bay 13 km to the south (Lausanne et al., 2017). Thus, isostatically-derived crustal tilt appears to be ruled out as an explanation because Chonat Lake is located only 3 km from Kanish and Waiatt Bays. Instead, as with Waiatt Bay, this may be a consequence, in part, of compaction and multiple paleobeach subsidence events over the millennia, or may indicate that the butterclams are not from the top of their tidal range as assumed in this paper for establishing a conservative estimate of the lowest RSL position.

Care is required in interpreting specific sea-level indicators and placing them in a regional context because of factors such as consolidation, slumping and tectonically-induced vertical crustal displacement. Nevertheless, in this study these effects do not appear to exceed 2 m in magnitude for specific observations and discrepancies can be identified during analysis and construction of a regional sea-level curve. The discrepancies in the elevations of some sea-level indicators do provide potential targets for further investigation with LiDAR imagery and other techniques to search for potential surface-breaking active crustal faults.

#### 4.4. Sea level history and paleogeography

The sea-level history of the region resulted in very significant changes in regional paleogeography. Shoreline locations suitable for human occupation shifted rapidly with marine regression. In the very early post-glacial period most of the 'Quadra archipelago'

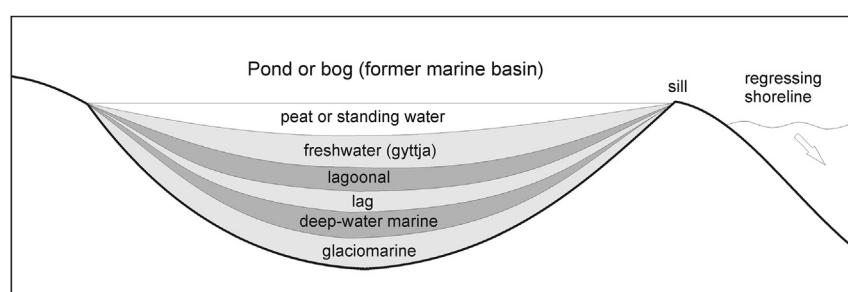


Fig. 22. Schematic of the sediment deposition sequence occurring during a typical marine regression.

shorelines were rocky and steep (Fig. 23). Only a few areas exhibited gentle terrain and protection from the prevailing (northwest and southeast) winds and waves. During late post-glacial times (ca. 13,000 to 10,000 years ago) the configuration of the Quadra area was similar to that of today with paleoshorelines within 30 m elevation and, generally, within 200 m horizontal distance from the modern shore.

The relict beaches at ca. 4, 10 and 30 m above the present shoreline (see section 3.4) suggest intervals of reduced rates of relative sea-level fall and may correlate with mountain glacier readvances (Mood and Smith, 2015; Friele and Clague, 2002; Clague and James, 2002). Explicit surface-loading calculations of a visco-elastic Earth model (e.g., Clark et al., 2014; James et al., 2000, 2009b), incorporating known constraints on Late Pleistocene glacial mass changes in the Coast Mountains, would resolve the potential contribution from this effect, but are beyond the scope of this paper. Similarly, it is possible that the inferred 1–2 m transgression at about 11,400 years ago, based on the Village Bay Lake cores, has an origin in glacier fluctuations in the Coast Mountains, but further investigation is required.

Alternatively, the proposed stillstands or slowstands could reflect rapid sea level rise due to meltwater pulses. The ages of the ~10 m and ~30 m terraces on Quadra (Appendix 1, Fig. 20) fit well to the 12,800–12,550 and 13,150–12,900 meltwater pulses described by Khanna et al. (2017). The terraces could thus reflect periods of time when the rate of global eustatic sea level rise matched local isostatic rebound.

#### 4.5. Application of sea level history to archaeological research

Integration of the Quadra sea level history with LiDAR models has aided the prospection for early archaeological sites. Using surface reconnaissance and shovel testing in areas of high archaeological potential on raised marine terraces and paleo-shorelines

we have located dozens of archaeological sites (Lausanne et al., 2017; Lausanne, 2018; Vogelaar et al., 2017; Vogelaar, 2017). As a refined sea-level history provides a potential means of dating some inland archaeological sites (cf. Breivik, 2014; Svendsen and Mangerud, 1987), several Quadra Island sites could date as early as ca. 12,900 years ago based on the relative sea-level history presented here. The Crescent Road raised beach site (EbSh-81), at ca. 10–12 m ahht, contains a rich microblade technology component dating to ca. 6500 years ago and a small number of stone tools from the underlying deltaic deposits. The latter were recovered within a silt layer containing the marine diatoms *Cosconodiscus* sp., *Plagiogramma staurophorum* and *Coccineis costata* as well as casts of marine shellfish, including cockles and other clams (Fedje et al., 2016). Charcoal in direct association with a shellfish cast in these deltaic deposits was dated to ca 12,700 years ago (UCI, 193684). These data, and reference to the Quadra sea-level history detailed here, indicate human occupation to at least ca. 12,700 years ago. Examples of other archaeological sites located using sea level and LiDAR imagery include Yeatman Bay (EbSh-98) where the lower component, at ca. 3.5 m elevation, dates from ca. 10,960 to 10,400 years ago (UCI, 193676, 193680) and Lactarius Road (EaSh-81), on a 26-m terrace, where the lower component dates to ca. 12,900 years ago based on RSL history.

A number of Quadra Island intertidal sites with lag deposits of stone tools initially suggested sea level might have fallen below modern levels during early to middle Holocene time, consistent with the tentative lowstand inferred by James et al. (2005). The more detailed sea level history described here suggests that sea level may not have fallen below present. Most of the time-diagnostic lithic artifacts (e.g. microblade cores) observed in intertidal context at these sites are of mid-Holocene age (Fedje et al., 2016). Historic A-Frame log yarding, stream and wave erosion of paleo-terraces, sediment compaction and subsidence provide ways to deliver artifacts to the present-day intertidal zone



**Fig. 23.** Map showing configuration of Quadra Island environs at ca. 14,300 years ago (in green tones) and modern configuration (in grey tones). Base map prepared by Keith Holmes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Taylor, 2009; Mathewes and Clague, 1994; Rogers, 1980). An example of ongoing erosion of a subsided terrestrial landform can be seen at site EbSh-23 where wave action is washing stone tools out of a 2000-year-old paleosol with a present elevation below the modern high tide level. Similarly, at site EaSh-75, in Village Bay, wave action is eroding a 6000-year-old stone tool-rich archaeological component out of a 5-m terrace (Fedje et al., 2016). Finally, at site EbSh-98 at Yeatman Bay large numbers of artifacts are found in the active stream channel and eroding out of a 4 m aht terrace 30–40 m from the modern shore.

## 5. Conclusions

A refined RSL history, building on the northern Strait of Georgia RSL curve derived by James et al. (2005), spans the past 14,300 years. Marine shorelines dating to the time of earliest post-glacial emergence are at least 197 m above present-day sea-level. The duration of this transgressive high stand is not known. The presence of prominent raised marine terraces at elevations of 26–30 m, 10–14 m and ca. 3–6 m above the modern shoreline suggest that the rapid fall in RSL during early post-glacial time was interrupted by sea-level stillstands or slowstands. These were possibly generated by regional glacial fluctuations, tectonic subsidence or by a rapid rate of eustatic sea level rise during global meltwater pulses arising from climatic variations such as the Younger Dryas. Following the sea-level fall to around 2 m elevation, a minor transgression of one or two metres may have occurred around 12,000 to 11,400 years ago. This was followed by a slow regression through the Holocene to modern levels.

The sea-level history presented here provides critical input for efficient discovery and cataloging of late Pleistocene and early Holocene archaeological sites on ancient raised shorelines (Fedje et al., 2016; Lausanne, 2018; Vogelaar, 2017). The rapid fall during early post-glacial time results in substantial challenges to locating archaeological sites as any record would be thinly spread across ephemeral shorelines. However, the preliminary evidence for sea level stillstands or slowstands within this time period provides targets with higher potential for locating early post-glacial archaeological sites. After ca. 12,000 years ago the reduced rate of RSL fall increases the potential for archaeological site discovery, especially with use of terrain imaging models from LiDAR. This is attested to by success in locating a number of archaeological sites on raised marine terraces with the aid of LiDAR imagery.

## Acknowledgments

The research reported on here was conducted in territories of the We Wai Kai, Wei Wai Kum, K'ómoks, Kwiakah, Klahoose and Xwemalkhwu First Nations. Funding and logistical support was provided by Eric Peterson and Christina Munck through the Tula Foundation and Hakai Institute. Logistical support was also provided by the Department of Anthropology at the University of Victoria. Work reported here was conducted under permits from the BC Archaeology Branch (#2014-0046) and BC Parks (#107261). A number of people assisted us with the isolation basin coring including Callum Abbott, Paul Bishop, Jenny Cohen, Travis Crowell, Bryn Fedje, Tom and Jem Hollanders, Joanne McSporran, Cecilia Porter and Colton Vogelaar. Keith Holmes, Alex Lausanne and Kirsten Mathison conducted RTK GPS surveys for data point elevations. Alex Lausanne and Colton Vogelaar prepared GIS maps in support of the paleoecological and archaeological research program. Jenny Cohen identified seed species from isolation basin cores. We extend a heartfelt thanks to Dana Lepofsky, Ginevra Toniello, Christine Roberts, Louis Wilson and the rest of the 'Clam Garden' team who shared data from their research on Quadra

Island. We also thank Interfor Corporation for permitting use of LiDAR imagery from Elk Bay. Martin Margold and two anonymous reviewers are thanked for very thorough reviews that helped to substantially improve the manuscript. This is Natural Resources Canada contribution number 20180005.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.quascirev.2018.05.018>.

## References

- Battarbee, R.W., 1986. Diatom Analysis. In: Birgland, B.E. (Ed.), *Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley and Sons, Chichester, U.K., pp. 527–570.
- Baxter, R.E., 1971. Earthquake Effects on Clams of Prince William Sound. The Great Alaska Earthquake of 1964. *Biology*. National Academy of Science Publication No. 1604. National Academy of Sciences, Washington, DC, pp. 238–245.
- Billets, S., 1998. JMC Environmentalist's Subsoil Probe. Report on File. U.S. Environmental Protection Agency, Washington DC. [https://archive.epa.gov/nrmrl/archive-ett/web/pdf/01\\_vr\\_clement.pdf](https://archive.epa.gov/nrmrl/archive-ett/web/pdf/01_vr_clement.pdf).
- Breivik, H.M., 2014. Palaeo-oceanographic development and human adaptive strategies in the Pleistocene-Holocene transition: a study from the Norwegian coast. *Holocene* 24, 1478–1490.
- Campeau, S., Pienitz, R., Hequette, A., 1999. *Diatoms from the Beaufort Sea Coast, Southern Arctic Ocean (Canada): Modern Analogues for Reconstructing Late Quaternary Environments and Relative Sea Levels*. J. Cramer Press, Stuttgart, p. 244.
- Clague, J.J., 1983. Glacio-isostatic effects of the Cordilleran ice sheet, British Columbia, Canada. In: Smith, D.E., Dawson, A.G. (Eds.), *Shorelines and Isostasy*. Academic Press, London, pp. 321–343.
- Clague, J.J., Harper, J.R., Hebda, R.J., Howes, D.E., 1982. Late Quaternary sea levels and crustal movements, coastal British Columbia. *Can. J. Earth Sci.* 19, 597–618.
- Clague, J.J., Mathewes, R.W., Guilbault, J.-P., Hutchinson, I., Ricketts, B.D., 1997. Pre-Younger Dryas resurgence of the southwestern margin of the Cordilleran ice sheet, British Columbia, Canada. *Boreas* 26, 261–278.
- Clague, J.J., James, T.S., 2002. History and isostatic effects of the last ice sheets in southern British Columbia. *Quat. Sci. Rev.* 21, 71–87.
- Clark, J., Mitrovica, J.X., Alder, J., 2014. Coastal paleogeography of the California, Oregon, Washington and Bering Sea continental shelves during the latest Pleistocene and Holocene: implications for the archaeological record. *J. Archaeol. Sci.* 52, 12–23.
- Coan, E.V., Scott, P.V., Bernard, F.R., 2000. Bivalve seashells of western north America: marine bivalve mollusks from Arctic Alaska to Baja California. *Santa Monica Museum of Natural History Monographs*, 2, p. 764.
- Crowell, T., 2017. Settlement and Sea-Level Histories: Refining Holocene Sea-Levels in Kanish and Waiatt Bays, Quadra Island. Unpublished M.A. thesis. Simon Fraser University, Burnaby.
- Cumming, B.F., Wilson, S.E., Hall, R.I., Smol, J.P., 1995. *Diatoms from Lakes in British Columbia (Canada) and their Relationship to Lakewater Salinity, Nutrients and Other Limnological Variables*. J. Cramer Press, Stuttgart, 207 pp.
- Denys, L., 1992. A check-list of the diatoms in the Holocene deposits of the Western Belgian Coastal Plain with a survey of their apparent ecological requirements. *Service Géologique de Belgique* 246.
- Deur, D., Dick, A., Recalma-Clutesi, K., Turner, N.J., 2015. Kwakwaka'wakw "clam gardens": motive and agency in traditional Northwest Coast mariculture. *Hum. Ecol.* 43, 201–212.
- Eamer, J.B., Shugar, D.H., Walker, I.J., Lian, O.B., Neudorf, C.M., Tekla, A.M., 2017. A glacial readvance during retreat of the Cordilleran Ice Sheet, British Columbia central coast. *Quat. Res.* (Duluth) 87, 468–481.
- Falu, M.A., Allaire, N., Pienitz, R., 2000. *Freshwater Diatoms from Northern Québec and Labrador (Canada): Species-environment Relationships in Lakes of Boreal forest, forest-tundra and Tundra Regions*. J. Cramer Press, Stuttgart, p. 200.
- Fedje, D., Mackie, Q., Smith, N.F., Mackie, A.P., McSporran, J.B., Vogelaar, C., Lausanne, A., Abbott, C., 2016. Discovery Islands Landscape Archaeology Research Project: Annual Report for 2014 Field Season, HCA Permit 2014-0046. Report on File. British Columbia Archaeology Branch, Victoria.
- Fedje, D., Sumpter, I.D., Southon, J.R., 2009. Sea levels and archaeology in the Gulf Islands National Park Reserve. *Can. J. Archaeol.* 33, 234–253.
- Fedje, D.W., Josenhans, H., Clague, J.J., Barrie, J.V., Archer, D., Southon, J.R., 2005. Hecate Strait paleoshorelines. In: Fedje, D., Mathewes, R. (Eds.), *Haida Gwaii, Human History and Environment from the Time of Loon to the Time of the Iron People*. UBC Press, Vancouver.
- Foged, N., 1981. *Diatoms in Alaska. Bibliotheca Phycologia*. Band 53. J. Cramer Press, Vaduz, Germany, p. 316.
- Friole, P.A., Clague, J.J., 2002. Younger Dryas readvance in Squamish River valley, southern coast mountains, British Columbia. *Quat. Sci. Rev.* 21, 1925–1933.
- Groesbeck, A.S., Rowell, K., Lepofsky, D., Salomon, A.K., 2014. Ancient clam gardens increased shellfish production: adaptive strategies from the past can inform food security today. *PLoS One* 9 e91235. <https://doi.org/10.1371/journal.pone.091235>.

- 0091235.
- Guiry, M.D., Guiry, G.M., 2017. AlgaeBase. World-wide Electronic Publication. National University of Ireland, Galway.
- Hebda, R.J., Lian, O.B., Hicock, S.R., 2016. Olympia Interstadial: vegetation, landscape history, and paleoclimatic implications of a mid-Wisconsinan (MIS3) nonglacial sequence from southwest British Columbia, Canada. *Can. J. Earth Sci.* 53, 304–320.
- Hein, M.K., 1990. Flora of Adak Island, Alaska: Bacillariophyceae (Diatoms). *J. Cramer Press*, Berlin, p. 133.
- Hodgson, E.A., 1946. The British Columbia earthquake, June 23, 1946. *J. Roy. Astron. Soc. Can.* 40, 285–319.
- Holmes, K., 2015. Qsudra Island Archaeology LiDAR Survey 2015. Unpublished Report on File at Hakai.Org.
- Hustedt, F., 1953. Die Systematik der Diatomeen in ihren Beziehungen zur Geologie und Ökologie nebst einer Revision des Halobien-Systems. *Sven. Bot. Tidskr.* 47, 509–519.
- Hutchinson, I., James, T.S., Clague, J.J., Barrie, J.V., Conway, K.W., 2004a. Reconstruction of Late Quaternary sea-level change in southwestern British Columbia from sediments in isolation basins. *Boreas* 33, 183–194.
- Hutchinson, I., James, T.S., Reimer, P.J., Bornhold, B.D., Clague, J.J., 2004b. Marine and limnic radiocarbon reservoir corrections for studies of late- and postglacial environments in Georgia Basin and Puget Lowland, British Columbia, Canada and Washington, USA. *Quaternary Research* 61, 193–203.
- James, T.S., Clague, J.J., Wang, K., Hutchinson, I., 2000. Postglacial rebound at the northern Cascadia subduction zone. *Quat. Sci. Rev.* 19, 1527–1541.
- James, T.S., Hutchinson, I., Clague, J.J., 2002. Improved relative sea-level histories for Victoria and Vancouver, British Columbia, from isolation basin coring. *Geological Survey of Canada, Current Research* 7, 2002–A16.
- James, T.S., Hutchinson, I., Barrie, J.V., Conway, K.W., Mathews, D., 2005. Relative sea level change in the northern Strait of Georgia, British Columbia. *Géogr. Phys. Quaternaire* 59, 113–127.
- James, T.S., Gowar, E.J., Hutchinson, I., Clague, J.J., Barrie, J.V., 2009a. Sea-level change and paleogeographic reconstructions, southern Vancouver Island, British Columbia, Canada. *Quat. Sci. Rev.* 28, 1200–1216.
- James, T.S., Gowar, E.J., Wada, I., Wang, K., 2009b. Glacio-isostatic adjustment modeling of new relative sea-level observations from the northern Cascadia subduction zone, British Columbia, Canada. *J. Geophys. Res.* 114 <https://doi.org/10.1029/2008JB006077>, B04405.
- Johnson, S.Y., Blakely, R.J., Stephenson, W.J., Dadisman, S.V., Fisher, M.A., 2004. Active shortening of the Cascadia forearc and implications for seismic hazards of the Puget Lowland. *Tectonics* 23, TC1011. <https://doi.org/10.1029/2003TC001507>.
- Josenhans, H.W., Fedje, D.W., Pienitz, R., Southon, J.R., 1997. Early humans and rapidly changing Holocene sea levels in the Queen Charlotte Islands, Hecate Strait, British Columbia, Canada. *Science* 277, 71–74.
- Kelly, M.G., Bennison, H., Cox, E.J., Goldsmith, B., Jamieson, J., Juggins, S., Mann, D.G., Telford, R.J., 2005. Common Freshwater Diatoms of Britain and Ireland: an Interactive Key. Environment Agency, Bristol.
- Khanna, P., Droxler, A.W., Nittrouer, J.A., Tunnell, J.W., Shirley, T.C., 2017. Coralgal reef morphology records punctuated sea-level rise during the last deglaciation. *Nat. Commun.* 8, 1046 <https://doi.org/10.1038/s41467-017-00966>.
- Kowalewski, M., Casebolt, S., Hua, Q., Whitacre, K.E., Kaufman, D.S., Kosnik, M.A., 2017. One fossil record, multiple time resolutions: disparate time-averaging of echinoids and mollusks on a Holocene carbonate platform. *Geology* 46 (1), 51–54.
- Lausanne, A., 2018. Identifying and Interpreting Geoarchaeological Sites with High Prospecting Potential Using Aerial LIDAR, GIS and Sedimentological Analyses. Unpublished MSc thesis, University of Victoria, p. 97.
- Lausanne, A., Fedje, D.W., Walker, I.J., Mackie, Q., 2017. A multi-method approach to prospecting stranded paleo-coastal sites on Quadra Island, British Columbia. In: Poster Presented at the 82nd Annual Meeting of the Society for American Archaeology, Vancouver.
- Lepofsky, D., Smith, N.F., Cardinal, N., Harper, J., White, E.G., Bouchard, R., Kennedy, D., Salomon, A.K., Morris, M., Puckett, M., Rowell, K., McLay, E., 2015. Ancient shellfish mariculture on the Northwest Coast of North America. *Am. Antiqu.* 80, 236–259.
- Letham, B., Martindale, A., Macdonald, R., Guiry, E., Jones, J., Ames, K.M., 2016. Postglacial relative sea level history of the Prince Rupert area, British Columbia, Canada. *Quat. Sci. Rev.* 153, 156–191.
- Maroohasy, J., Abbot, J., 2007. Review of the Salinity Optima of the Diatom *Staurastraea* Pinnata: Implications for Water Reform in Australia. School of Medical and Applied Sciences, Central Queensland University, Noosa, Australia.
- Mathewes, R.W., Clague, J.J., 1994. Detection of large prehistoric earthquakes in the Pacific Northwest by microfossil analysis. *Science* 264, 688–691.
- Massey, A.C., Paul, M.A., Gehrels, W.R., Charman, D.J., 2006. Autocompaction in Holocene coastal back-barrier sediments from south Devon, southwest England. *Mar. Geol.* 226, 225–241.
- McCommon, J.W., 1977. Surficial geology and sand and gravel deposits of Sunshine Coast, Powell River, and Campbell River areas. British Columbia ministry of mines and petroleum Resources. *Bulletin* 65, 36.
- McLaren, D., Fedje, D.W., Hay, M., Mackie, Q., Walker, I.J., Shugar, D.H., Eamer, J.B., Lian, O.B., Neudorf, C., 2014. A Post-glacial sea level hinge on the central Pacific coast of Canada. *Quat. Sci. Rev.* 97, 148–169.
- McLaren, D., Martindale, A., Fedje, D.W., Mackie, Q., 2011. Relict shorelines and shell middens of the Dundas island archipelago. *Can. J. Archaeol.* 35, 86–116.
- Meidinger, D., Pojar, J., 1991. Ecosystems of British Columbia. Government of British Columbia. Ministry of Forests, Victoria, BC. Special Report Series 6.
- Menounos, B., Osborn, C., Clague, J.J., Luckman, B.H., 2009. Latest Pleistocene and Holocene glacier fluctuations in western Canada. *Quat. Sci. Rev.* 28, 2049–2074.
- Miettinen, A., Jansson, J., Aleinik, T., Haggen, G., 2007. Late Holocene sea-level changes along the southern coast of Finland, Baltic Sea. *Mar. Geol.* 242, 27–38.
- Mills, K., Mackay, A., Bradley, R., Finney, B., 2009. Diatom and stable isotope records of late-Holocene lake ontogeny at Indrepollen, Lofoten, NW Norway: a response to glacio-isostasy and Neoglacial cooling. *Holocene* 19, 261–271.
- Mood, B.J., Smith, D.J., 2015. Latest Pleistocene and Holocene behaviour of Franklin Glacier, Mt. Waddington area, British Columbia coast mountains, Canada. *Holocene* 25, 74–94.
- Morell, K.D., Regalla, C., Leonard, L.J., Amos, C., Levson, V., 2017. Quaternary rupture of a crustal fault beneath Victoria, British Columbia, Canada. *GSA Today (Geol. Soc. Am.)*. <https://doi.org/10.1130/GSAT291A.1>, v. 27.
- Myrho, H., Wright, E., 2005. Livingstone-Bolivia. PDF Report on File at the University of Michigan. Limnological Research Center. <http://lrc.geo.umich.edu/laccore/assets/pdf/sops/livingstone-bolivia.pdf>.
- Peltier, W.R., Fairbanks, R.G., 2006. Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record. *Quat. Sci. Rev.* 25, 3322–3337.
- Pienitz, R., Fedje, D.W., Poulin, M., 2003. Marine and Non-marine Diatoms from the Haida Gwaii Archipelago and Surrounding Coasts, Northeast Pacific, Canada. *J. Cramer Press*, Stuttgart, p. 146.
- Plafker, G., 1969. Tectonics of the March 27 1964 Alaska Earthquake. US Department of the Interior, Earthquake Series. US Government Printers, Washington, DC.
- Quayle, D.B., Bourne, N., 1972. The clam fisheries of British Columbia. Fisheries research board of Canada. *Bulletin* 179, 70.
- Reasoner, M.A., 1986. An inexpensive, lightweight percussion core sampling system. *Géogr. Phys. Quaternaire* 40, 217–219.
- Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hatta, C., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., Manning, S.W., Niu, M., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., van der Plicht, J., 2013. IntCal13 and Marine 13 radiocarbon age calibration curves 0–50000 years calBP. *Radiocarbon* 55, 1869–1887.
- Rogers, G.C., 1980. A documentation of soil failure during the British Columbia earthquake of July 23, 1946. *Can. Geotech. J.* 17, 122–127.
- Rogers, G.C., Hasegawa, H.S., 1978. A second look at the British Columbia earthquake of June 23, 1946. *Bull. Seismol. Soc. Am.* 68 (3), 653–676.
- Rosen, P., Segerstrom, U., Eriksson, L., Renberg, J., Birks, H.J., 2001. Holocene climatic change reconstructed from diatoms, chironomids, pollen and near-infrared spectroscopy at an alpine lake (Sjödijärvi) in northern Sweden. *Holocene* 11, 551–562.
- Ruhland, K.M., Smol, J.P., Paterson, A.M., 2015. Lake diatom responses to warming: reviewing the evidence. *J. Paleolimnol.* 54, 1–35.
- Shugar, D.H., Walker, I.J., Lian, O.B., Eamer, J.B., Neudorf, C., McLaren, D., Fedje, D.W., 2014. Post-glacial sea-level change along the Pacific coast of North America. *Quat. Sci. Rev.* 97, 170–192.
- Spaulding, S.A., Lubinski, D.J., Potapova, M., 2010. Diatoms of the United States. <http://westerndiatoms.colorado.edu>.
- Svendsen, J.I., Mangerud, J., 1987. Late Weichselian and Holocene sea-level history for a cross-section of western Norway. *J. Quat. Sci.* 2, 113–132.
- Taylor, G., 2009. The Quadra Story: a History of Quadra Island. Harbour Publishing, Madeira Park, p. 272.
- Toniello, G., Lepofsky, D., Smith, N.F., Neudorf, C., 2015. Quadra Island Clam Garden Project 2014–2015 Fieldwork in Kanish and Waiatt Bays, HCA Inspection Permit No. 2014-0095. Report on File, Archaeology Branch, Province of British Columbia, Ministry of Forests, Lands and Natural Resource Operations, Victoria, B.C.
- Toniello, G., Crowell, T., Lepofsky, D., Smith, N.F., Neudorf, C., 2016. Quadra Island Clam Garden Project 2015 Fieldwork in Kanish and Waiatt Bays, 2015 Report, BC Park Use Permit #107144. Report on File BC Parks, Province of British Columbia, Ministry of Environment, Victoria, B.C.
- Vogelaar, C., 2017. Using GIS Modelling as a Tool to Search for Late Pleistocene and Early Holocene Archaeology on Quadra Island, British Columbia. Unpublished M.A. thesis, University of Victoria, Victoria, Canada.
- Vogelaar, C., Mackie, Q., Fedje, D.W., 2017. Coastal predictive modelling for early period archaeological sites in a landscape subject to rapidly changing sea levels, Quadra Island, British Columbia. In: Poster Presented at the 82nd Annual Meeting of the Society for American Archaeology, Vancouver.
- Wilson, S.E., Cumming, B.F., Smol, J.P., 1996. Assessing the reliability of salinity inference models from diatom assemblages: an examination of a 219-lake data set from western North America. *Can. J. Fish. Aquat. Sci.* 53, 1580–1594.
- Zong, Y., Sawai, Y., 2015. Diatoms. In: Shennan, I., Long, A.J., Horton, B.P. (Eds.), *Handbook of Sea Level Research*. Wiley and Sons publishing, Oxford.