Sea Level change in the Gulf Islands National Park Reserve, southern British Columbia: implications for the interpretation of nearshore archaeological features

by

GLENDA JOAN WYATT

A Thesis Submitted to the Faculty of Social and Applied Sciences in Partial Fulfilment of the Requirements for the Degree of

MASTER OF SCIENCE

Royal Roads University
Victoria, British Columbia, Canada

Supervisor: AUDREY DALLIMORE

NOVEMBER, 2015

© GLENDA J. WYATT, 2015
COMMITTEE APPROVAL

The members of Glenda J. Wyatt’s Thesis Committee certify that they have read the thesis titled Sea Level change in the Gulf Islands National Park Reserve, southern British Columbia: implications for the interpretation of nearshore archaeological features and recommend that it be accepted as fulfilling the thesis requirements for the Degree of Master of Science:

Dr. Leslie King [signature on file]

Final approval and acceptance of this thesis is contingent upon submission of the final copy of the thesis to Royal Roads University. The thesis supervisor confirms to have read this thesis and recommends that it be accepted as fulfilling the thesis requirements:

Dr. Audrey Dallimore [signature on file]
Creative Commons Statement

This work is licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 2.5 Canada License. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-sa/2.5/ca/.

Some material in this work is not being made available under the terms of this licence:

- Third-Party material that is being used under fair dealing or with permission.
- Any photographs where individuals are easily identifiable.
Table of Contents

Creative Commons Statement ................................................................. 2
Dedication ................................................................................................. 8
Acknowledgements ................................................................................ 9
Notes .......................................................................................................... 10
Abstract ................................................................................................... 11
Introduction .............................................................................................. 12
  Paleo-sea Levels .................................................................................. 12
  Clam Gardens ....................................................................................... 15
  Future Sea Levels .................................................................................. 18
Literature Review ..................................................................................... 21
  Paleo-sea Levels .................................................................................. 21
  Paleoenvironments ................................................................................ 23
  Clam Gardens ....................................................................................... 24
  Influences of Global Climate Change .................................................... 27
  Future Sea Levels .................................................................................. 29
  Projected sea levels along the B.C. Coast ................................................ 30
  Influence of Anthropogenic Activities .................................................. 31
  Tectonic Influences .............................................................................. 31
Methods .................................................................................................... 33
  Sea Level Mapping ............................................................................... 33
  Isolation Basin ..................................................................................... 34
Results ....................................................................................................... 36
  Paleo-sea Levels .................................................................................. 36
  Isolation Basins .................................................................................... 43
  Clam Gardens ....................................................................................... 44
  Current Sea Levels at Fulford Harbour and Russell Island .................. 46
Discussion ................................................................................................. 52
  Paleo-sea Levels .................................................................................. 52
  Clam Gardens ....................................................................................... 54
  Future Sea Levels .................................................................................. 59
Conclusion ................................................................................................. 60
Appendix A ................................................................................................. 75
List of Figures

Figure 1. Post glacial sea level curves for different parts of the British Columbia coast over the past 16,000 years, post- Fraser Glaciation (McLaren, 2008, figure 9). A – Kitimat (Clague, 1984; Fedje, Christensen, Josenhan, McSporran, & Strang, 2005); B – Prince Rupert/Port Simpson (Archer, 1998; Clague, 1984; Eldridge & Parker, 2007; Fedje et al., 2005); C – Southern Haida Gwaii (Fedje et al., 2005); D – Central Hecate Strait (Hetherington, 2002); E – Northern Hecate Strait (Hetherington, 2002); F – Global eustatic sea level rise (Fairbanks, 1989). Further work has been done since this figure was compiled and this will be discussed in the literature review.

Figure 2. West coast of British Columbia. The location of the clam gardens to be discussed are marked by the red star. Imagery sources are cited on the map. Base map copyright © Esri.

Figure 3. Gulf Island National Park boundaries. Parks Canada protected marine areas are the marine extents of the GINPR areas shown above. Boundaries provided by S. Augustine, Parks Canada. Labels for groups of islands from Parks Canada (2015b). The two case study clam garden sites, Fulford Harbour and Russell Island, are marked by red and yellow stars respectively. Base map copyright © Esri.

Figure 4. South end of a clam garden in Fulford Harbour, Saltspring Island, with the Saanich Peninsula in the distance (see Figure 3). The main parts of the clam garden are labelled.

Figure 5. Location of clam garden GINPR case studies on Saltspring Island (Fulford Harbour – red star) and Russell Island (yellow star). The lighter water areas along the shore of Fulford Harbour indicate shallow sediment waters. The resolution of the image does not allow for the distinction of the clam garden on the north side of Russell Island. Base map copyright © Esri.

Figure 6. Diagram of the Cascadia Subduction Zone (CSZ) (Yorath, Kung, & Franklin, 2002).

Figure 7. Sea level change and corresponding changes in vegetation assemblages from Yorath, Kung, & Franklin (2002). The red star indicates the location of the clam garden case study sites in GINPR. The time slices move from immediately post glacial at 14,500 years before present, and through 6,000 years before present when sea level stabilized to be close to present day levels. The images show the changes in ice cover, vegetative assemblage and sea level. Changes in vegetation can occur relatively quickly and likely indicate a change in climate as glacial ice leaves the area, and present day seasonality is established.

Figure 8. Cross section of clam garden structure as compared to a non-walled beach. The volume of available habitat is increased with the rock wall. Diagram adapted from Groesbeck et al. (2014) Figure 3.
Figure 9. Published paleo-sea level curves from the coast of British Columbia. The variable responses to deglaciation along the coast can be seen. References noted in legend.................................................................37

Figure 10. Present day sea level. The black and white areas represent topography above the waterline. The case study sites are marked by the yellow and red stars. White areas indicate a lack of data in intertidal zone.................................................................39

Figure 11. Sea level 3,500 years before present when glacio-isostatic rebound had likely ceased in the GINPR area, 1.25 metres below current levels. This indicates that, if clam gardens were in use at the time, there may be evidence of them now submerged below current sea levels. Climatic conditions were similar to present day. White areas indicate a lack of data in intertidal zone.................................................................40

Figure 12. Sea level 5,000 years before present when glacio-isostatic rebound had likely ceased in the GINPR area, 4 metres below current levels. Climatic conditions were similar to present day.................................................................40

Figure 13. Sea level 8,000 years before present, at 30 metres below current levels. This time slice represents deglaciation when sea levels were much lower than today’s due to sea water frozen into waning glaciers and ice sheets, and the crust exhibited depression due to the weight of the recently melted ice sheets. Climatic conditions were warmer and drier than present. .................................................................41

Figure 14. Sea level 9,079 years before present, 44 metres below current levels. There may be archaeological evidence for clam gardens along these now submerged shorelines. There is evidence for the Salish Sea, including the nearby San Juan Islands, being populated during this time (Kenady, Wilson, Schalk, & Mierendorf, 2011; Waters et al., 2011). Climatic conditions were warmer and drier than present day. .................................................................41

Figure 15. Sea level 9,850 years before present, 55 metres below current levels. Between this time and the sea level highstand in Figure 17, the crust rebounded from glacio-isostatic depression immediately post-glaciation.................................................................42

Figure 16. Sea level 11,750 years before present, 30 metres above current levels. At this time, the crust would have been severely depressed from the weight of glacial ice, allowing inundation of the sea into the area. Examining the location of these shorelines could provide more archaeological evidence for clam gardens. Climatic conditions would be warmer and much drier than present day. .........................42

Figure 17. Sea level 12,200 years before present, 75 metres above current levels. At this point in time, many of the islands surrounding Saltspring Island were submerged, including Russell Island. In addition, it shows that the current area known as Saltspring Island was once at least three islands. .................................................................43

Figure 18. Locations of potential isolation basin sites on Saltspring Island. Sources for imagery indicated on map. Base map copyright © Esri. .................................................................44
Figure 19. Locations of clam gardens currently mapped in the literature. Literature sources for these sites are Harper (2012) as cited in Augustine & Dearden (2014); Cardinal (2014); Fedje & Smith (2010); Harper et al. (1995); Lepofsky et al., (2015). Base map copyright © Esri .................................................................46

Figure 20. Rock wall for clam garden in Fulford Harbour on Saltspring Island, British Columbia, looking south to the Saanich Peninsula across Satellite Channel, June 15, 2015 (Figure 18). ........................................................................................................47

Figure 21. The Russell Island clam garden site looking to the south, onto the north shore of Russell Island. The rock wall is just visible above the waterline in the foreground of the photo. Note this photo was taken within 15 minutes of the photo in Figure 20, showing the noticeable difference in wall height, which may suggest that the Russell Island site was built at an earlier time, during a lower sea level stand than at the construction time of the Fulford Harbour site. .................................................................48

Figure 22. Rock wall for clam garden on Russell Island, B.C. The white line indicates the submerged wall, which was under water at the same time as the wall at Fulford Harbour was exposed on June 15, 2015. ........................................................................................................48

Figure 23. Sea level prediction for 2100, 0.94 metres above current sea level. While not visually striking, the small red areas along the coast line show where the first areas of sea level inundation will be. ........................................................................................................48

Figure 24. Sea level prediction for 2300, 3.6 metres above current sea level. Focusing on Russell Island, it can be seen that several parts of the shore line would be submerged at this level. ........................................................................................................50

Figure 25. Sea level prediction of 11.5 metres of sea level for the year 2500. This is the highest sea level prediction made by the IPCC (Church et al., 2013). The highest high value is used to emphasize the significant impact sea level change will have on B.C. coastal communities in the next 400 years due to global climate change. This shows a significant inundation of water at the upper end of Fulford Harbour and this would have an impact on the current community surrounding the harbour. In addition, Russell Island has become three islets. ........................................................................................................51

Figure 26. Drowned forest at Island View Beach on Eastern Vancouver Island. It was temporarily exposed after a spring wind storm in 2008. Note that this feature is not always exposed on the beach. During spring and summer 2015 for example, the feature could not be seen, presumably temporarily covered over again by the sands of the onshore sediment transport during a calm spring and summer season. White arrows indicate locations of drowned trees. Photos courtesy of Dr. A. Dallimore, Royal Roads University. Paleo-sea level researcher Dr. Tom James, of Natural Resources Canada, is pictured in the photo. ........................................................................................................58
List of Tables

Table 1. Paleo climate for southern Vancouver Island derived from vegetation regimes (Pellatt et al., 2001). ........................................................................................................................................23

Table 2. Model spread of global sea level change for low, medium and high greenhouse gas emissions scenarios (values extracted from Table 13.8 from Church et al., 2013). The predictions take into account thermal expansion, glaciers, the Greenland ice sheet and the Antarctic ice sheet. All predictions are in metres [m]. .........................30

Table 3. Relative sea level rise by 2100 for selection locations in British Columbia (adapted from Table 1 from Bornhold, 2008). These values were derived from historical tide gauge data. .................................................................31

Table 4. Paleo-sea level values from south-eastern Vancouver Island paleo-sea level literature. Values are relative to current sea level (RSL). The value for 3,500 provides recent data from within GINPR (Fedje et al., 2009). The values from James et al., (2009) are the most recent and closest in proximity to the study area. The values from Mosher & Hewitt (2004) are from an earlier study and slightly further away (eastern Juan de Fuca Strait) but provide values to fill in the time gaps near 9,000 and 10,000 YBP. Values that were taken from samples are referenced and include ± errors. Values taken from the publication’s text do not have error values. .................................................................................................................................39

Table 5. Predictions for sea level rise. Values are relative to current sea level. The 2100 value is the highest value for Victoria from Table 3. The 2300 and 2500 are global predictions and therefore are only a wide approximation for the region of GINPR. The value for 2500 is the highest value from a semi-empirical model run by Jevrejeva et al. (2012a) (as cited in Church et al., 2013). .........................................................49
Dedication

This thesis is dedicated to my parents, Doreen and James Wyatt, who exposed me to the natural world at a young age and ultimately began my love of and passion for the environment. Also to my partner-in-crime, Karl Rhynas, whose constant encouragement and love gave me the confidence to undertake this next step in my education.
Sea Level Change in the Gulf Islands National Park Reserve

Acknowledgements

This thesis would not be possible without contributions from all of those involved with the Clam Garden Network (www.clamgarden.com), in particular Nicole Smith, Skye Augustine and Nathan Cardinal of Parks Canada, and my supervisor Dr. Audrey Dallimore and committee member Dr. Leslie King, both of Royal Roads University. I would also like to acknowledge the First Nations communities involved in the Clam Garden project. Fieldwork funding was provided by grants to Dr. Dallimore from NSERC Promoscience and Canada Foundation for Innovation. Robert Kung of Natural Resources Canada provided data and GIS technical assistance. Dr. Thomas James of Natural Resources Canada provided information regarding paleo-sea levels for the area. Dr. Iain McKechnie for an extremely valuable external evaluation. Fellow Royal Roads University Masters candidates Kimberly Cousineau, Carrie McIntosh, and Malcolm Nicol provided invaluable support and assistance throughout the process. The Royal Roads University MEM 2013 cohort is a great group of individuals and I thoroughly enjoyed the time I spent with them and value the long-term friendships created. My running group, the Deep Cove Divas, for their friendship and endless encouragement. Finally, my invaluable spouse, Karl Rhynas for editorial and never-ending emotional support as well as taking care of ‘everything else’ around our home. My heartfelt thanks goes out to all of these people.
Notes

Maps throughout this paper, including the satellite imagery were created using ArcGIS® software by Esri. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved. Satellite imagery sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS User Community.

An important note for this thesis is that most of the paleo dates provided are $^{14}$C years before present (YBP). The age indicated is directly related to the amount of radiocarbon in the sample and assumes the radiocarbon half life is 5568 years and the radiocarbon concentration has been the same as it was in 1950 (Waikato Radiocarbon Dating Laboratory, 2015). If the date is not radiocarbon years, it will be noted as calendar years.
Abstract

Sea level along the B.C. coastline has changed dramatically over the past 10,000 years due to isostatic rebound following deglaciation from the Fraser Glaciation (Clague & James, 2002). In the future, sea levels globally are also predicted to rise according to the Intergovernmental Panel on Climate Change (IPCC) (2014), due to climate change. Lemmen et al. (2008), suggest that in the near future some B.C. coastal communities will have to deal with changes in shorelines due to rising sea levels, and hence erosional patterns, modifications to ecosystems and habitats, and potentially an altered marine food supply. This thesis examines local paleo-sea level curves for Southern Georgia Strait and the Southern Gulf Islands constructed from a literature search, GIS analysis, and archaeological data from clam gardens. Clam gardens are rock walls, created by First Nations, that expand the natural habitat of clams in a sustainable and environmentally responsible manner. Pollen maps of the area from the literature are used to add landscape change to GIS-modelled paleo-sea level “shorescapes”. This project is part of an on-going research project undertaken with Parks Canada, in partnership with Royal Roads University and the Clam Garden Network, in the Gulf Island National Park Reserve (GINPR) to research and potentially restore First Nations nearshore archaeological features in GINPR.
Introduction

Paleo-sea Levels

The earth has undergone climatic fluctuations throughout its existence and this includes changes in sea level. Climate and ocean circulation have had periods of abrupt changes throughout prehistory (Lemmen et al., 2008). During the last 3 million years, global relative mean sea level has been, on average, 5 metres higher than current levels when global mean temperature was 2 °C warmer than pre-industrial times (Church et al., 2013). This is likely due to periodic deglaciation of parts of the Antarctic ice sheets in addition to near-complete deglaciation of the Greenland ice sheet (Church et al., 2013). Regions in British Columbia (B.C.) responded quite differently during the period following the end of the Fraser Glaciation, due to localized glacial melt and variable crustal isostatic response, due to differences in mantle viscosity (Clague & James, 2002). While global sea level rose 120 metres during that time, portions of the coast experienced a 200 metre drop in sea level due to variable crustal response to deglaciation (Bornhold, 2008). Consequently, along the B.C. coast, relative sea level varies significantly regionally and temporally over the past 16,000 years (Figure 1).

This study investigates and synthesizes paleo-sea level changes described in the literature, throughout the Strait of Georgia, which is part of the Salish Sea, in which the study area of GINPR is located (Figure 2 and Figure 3). The Salish Sea refers to “the inland marine sea comprised of Juan de Fuca Strait, Strait of Georgia, Puget Sound and their connecting channels, passes and straits” (Government of British Columbia, 2010). Time slice paleo-sea level maps of changing shorelines in GINPR are created from data in the B.C. coastal paleo-sea level literature. In this thesis, these data are modelled in
GIS. The resulting maps can be applied to dating and envisioning the evolution of nearshore indigenous aquaculture features in GINPR, such as clam gardens.

Figure 1. Post glacial sea level curves for different parts of the British Columbia coast over the past 16,000 years, post- Fraser Glaciation (McLaren, 2008, figure 9). A – Kitimat (Clague, 1984; Fedje, Christensen, Josenhan, McSporran, & Strang, 2005); B – Prince Rupert/Port Simpson (Arch, 1998; Clague, 1984; Eldridge & Parker, 2007; Fedje et al., 2005); C – Southern Haida Gwaii (Fedje et al., 2005); D – Central Hecate Strait (Hetherington, 2002); E – Northern Hecate Strait (Hetherington, 2002); F – Global eustatic sea level rise (Fairbanks, 1989). Further work has been done since this figure was compiled and this will be discussed in the literature review.
Figure 2. West coast of British Columbia. The location of the clam gardens to be discussed are marked by the red star. Imagery sources are cited on the map. Base map copyright © Esri.
Clam Gardens

Sea level dictates habitat distribution and migration patterns for humans and animals (Barrie & Conway, 2012; Erlandson et al., 2007; Hetherington & Barrie, 2003; Mackie, Fedje, McLaren, Smith, & McKechnie, 2011). In addition, knowledge of paleo-sea level patterns aids in marine and coastal engineering and planning (James, Hutchinson, Barrie, Conway, & Mathews, 2005). Determining paleo coastlines may also aid in locating possible past human settlements and nearshore archaeological features (Barrie & Conway, 2012; Fedje, Sumpter, & Southon, 2009; Grier, Dolan, Derr, & McLay, 2009).

For example, recently characterized “clam garden” features were created by First Nations people in pre-history, and are of emerging interest since they can provide...
Sea Level Change in the Gulf Islands National Park Reserve

valuable information regarding human settlements, indigenous peoples’ practices and how changing sea levels have impacted coastal populations in the past (Anderson & Parker, 2009; Groesbeck, Rowell, Lepofsky, & Salomon, 2014; Harper, Haggerty, & Morris, 1995). Clam gardens are composed of human created rock walls built along the coastline which artificially, but sustainably, increase the natural habitat for clams (Figure 4). These archaeological features are now being identified all along the B.C. coast to Alaska, and south to the Canadian and American Salish Sea areas (Deur, Dick, Recalma-Clutesi, & Turner, 2015; Lepofsky et al., 2015). Although precise timing is unknown, clam gardens were built by coastal indigenous populations over the past several millennia, during the late Holocene and generally consist of rock-walled terraces in the intertidal zones (Lepofsky et al., 2015). These structures have only been recently described in modern literature with the help of Coast Salish elders and knowledge keepers (Deur, Dick, Recalma-Clutesi, & Turner, 2015; Lepofsky et al., 2015). It has been discovered recently that they were a method for increasing the population of clams for food harvesting (Groesbeck et al., 2014).

Figure 4. South end of a clam garden in Fulford Harbour, Saltspring Island, with the Saanich Peninsula in the distance (see Figure 3). The main parts of the clam garden are labelled.
This thesis is part of a 2015 Parks Canada five year “Clam Garden Restoration Study” to identify, characterize and possibly restore clam garden features in the Gulf Islands National Park Reserve (GINPR), in the southern Gulf islands area of the B.C. coast (Figure 3) (Parks Canada, 2015a). Applying paleo-sea level modelling in the case study area near clam garden features in GINPR, using published data of paleo-sea level curves. In addition, the thesis also addresses how the combination of known paleo-sea level curves and GIS modelled time slice paleo-sea level maps may be used to reconstruct local paleo environments where First Nations have resided for thousands of years. The thesis also investigates how future sea level modelling data can provide compelling visual reminders of likely global climate change impacts in GINPR. GINPR is a particularly vulnerable area in southern B.C. in regards to rising sea levels in the late Holocene, especially given the tectonic influences on sea level (Fedje et al., 2009; Verdonck, 2006). Recent observations of significant erosion at shell midden sites in GINPR may indicate sea level rise is currently impacting the region (I. McKechnie, 2015, pers. comm.).

This project has policy and community implications through the Action on the Ground research project of GINPR. The objectives of the Action on the Ground research project include undertaking restoration of two clam garden beds in GINPR and area, along the western shore of Fulford Harbour, Saltspring Island and the northern shore of Russell Island (i.e. red star and yellow starred locations on Figure 5). Under the Action on the Ground Clam Garden project, GINPR proposes to manage these two case study clam garden restoration sites over the next five years (2015-2020); recommend management techniques, both traditional and scientific, to improve future intertidal ecosystems; and connect with local Coast Salish First Nations around clam garden and
coastal resource indigenous practices (Cardinal, 2014). The Action on the Ground Clam Garden project, and this thesis ultimately will be a part of Parks Canada in-park resources planning, as well as the public outreach and education program of Parks Canada and an on-going NSERC PromoScience Grant to Royal Roads University, “Learning By the Sea” (2013-2016).

Figure 5. Location of clam garden GINPR case studies on Saltspring Island (Fulford Harbour – red star) and Russell Island (yellow star). The lighter water areas along the shore of Fulford Harbour indicate shallow sediment waters. The resolution of the image does not allow for the distinction of the clam garden on the north side of Russell Island. Base map copyright © Esri.

**Future Sea Levels**

Using the IPCC modelled projections of global sea level rise, GIS maps of future shorelines in the study area are also presented in this thesis. Eustatic (global) sea levels are currently rising and are predicted to rise further in the near future, due to global climate change (IPCC, 2014). Consequently, many British Columbia coastal communities will be subject to changes in erosional patterns, modifications to nearshore ecosystems and potentially an altered food supply (Bornhold, 2008; Lemmen et al., 2008). The
factors that will lead to the rise of sea level in coastal B.C. in the future due to global climate change “include melting of ice caps, continental ice sheets and mountain glaciers, global changes in ocean water temperature and salinity (steric effects), and the variations in the storage of water in land-based reservoirs” (Thomson, Bornhold, & Mazzotti, 2008, p.iv).

In addition, in B.C., there is a tectonic component to sea level change due to the subduction of the Cascadia Subduction Zone (CSZ), which is located just offshore of the west coast of Vancouver Island. Consequently, parts of southern B.C., are now rising by several mm/year, due to the strain of the subducting plate causing crustal uplift in some areas. This can mitigate the impact of rising sea levels due to global climate change where the crustal uplift is nearly equal or greater than the predicted sea level rise due to global climate change (Leonard et al., 2007; Verdonck, 2006). The tectonic regime here involves the oceanic Juan de Fuca tectonic plate subducting beneath the continental tectonic plate (Figure 6). In geologic time, the CSZ is known to have produced megathrust earthquakes of M 8 and 9, and one megathrust earthquake and accompanying tsunamis in historical time, on Jan. 21, 1700 AD (Clague & Bobrowsky, 1994; Enkin, Dallimore, Baker, Southon, & Ivanochko, 2013). CSZ megathrust earthquakes can also result in sea level rise of up to several meters concurrent with the earthquake, as the strain between the subducting Juan de Fuca plate and the overriding North American plate is released. This phenomena is referred to as co-seismic subsidence (Leonard et al., 2007) and likely occurred at the study site, since CSZ megathrust earthquakes are thought to have occurred approximately every 500 to 1000 years in southern B.C., since deglaciation (Enkin et al., 2013). The current uplift in the northern Strait of Georgia is
estimated to be 0.25 mm/yr (James et al., 2005). This uplift is due to the subduction zone building strain, and in some areas of the B.C. coast is therefore mitigating sea level rise due to global climate change (Lemmen et al, 2008).

Figure 6. Diagram of the Cascadia Subduction Zone (CSZ) (Yorath, Kung, & Franklin, 2002).
Literature Review

Paleo-sea Levels

The Fraser Glaciation, the most recent glaciation in British Columbia, began approximately 25,000 to 30,000 years ago (Clague, 1989, as cited in Barrie & Conway, 2012). There was significant crustal displacement during this glaciation and the subsequent deglaciation, due to ice loading followed by crustal isostatic rebound of up to 100 meters in the southern B.C. area (Clague, Harper, Hebda, & Howes, 1982; Dallimore et al., 2008). Juan de Fuca Strait was deglaciated by 13,600 years before present (YBP) and the Fraser Glaciation came to an end about 10,000 YBP, resulting in the ice cover currently present in British Columbia (Dallimore et al., 2008; James et al., 2009). The glacio-isostatic crustal rebound of southern Vancouver Island ceased about 6,000 YBP (Barrie and Conway 2002; Dallimore et al., 2008). The coastal ocean dynamics currently in place around Vancouver Island were established approximately 11,500 calendar YBP as ice receded from the outer coast (Dallimore et al., 2008).

The degree of sea level change on the British Columbia coast, as well as the direction of change (rising or falling), varied depending on the region. These changes were a result of the elastic thickness of the lithosphere, local mantle viscosity, global eustasy and the change in thickness and position of the glaciers (Hetherington & Barrie, 2004). Earth’s mantle responded in a variable manner in response to the isostatic unloading along the Cascadia subduction zone. The total response is made up of an early response controlled by a low viscosity upper mantle and a later response controlled by the lower, more viscous, mantle (James et al., 2005). The north coast (Hetherington, Barrie, Reid, MacLeod, & Smith, 2004), the central mainland coast (Fedje & Josenhans, 2000;
McLaren et al., 2014; Shugar et al., 2014), Georgia Strait (Barrie & Conway, 2002; James et al., 2005) and the outer coast of Vancouver Island (Dallimore et al., 2008) all responded differently to deglaciation. For the mainland of British Columbia, relative sea level fell rapidly between 10,000 and 9,000 YBP. In contrast, the relative sea level rose 75m in northern Hecate Strait during the same interval. In Queen Charlotte Sound relative sea level rose gradually after 13,000 YBP (Hetherington et al., 2004). McLaren et al., (2014) show that the sea level curve for western Hakai Pass, located between Vancouver Island and Haida Gwaii, has remained relatively stable over the last 15,000 years, staying within 10 metres of present sea level. A similar trend is also shown for the Dundas Islands, located on the north coast of B.C. (McLaren, Martindale, Fedje, & Mackie, 2011).

Another example of differences in sea level along the coast, is that the sea level lowstand on the west coast of Vancouver Island occurred approximately 13,500 YBP (Dallimore et al., 2008). This is approximately 1,000 years before the lowstand in Georgia Basin, which is 100 km to the east (James et al., 2005). On southern Vancouver Island, sea level dropped below present levels approximately 2,000 years earlier than in the northern Strait of Georgia and 1,000 years earlier than in the central Strait of Georgia. Victoria and the central Strait of Georgia reached low stand around the same time but the level at Victoria is about 15 metres deeper. At Victoria, the sea level rose within two metres of its present level approximately 200 years after the same change in central and northern Strait of Georgia (James et al., 2009). Glacio-isostatic crustal is thought to have ceased about 6,000 YBP on the west coast of Vancouver Island, and also likely ceased
about this time or a few centuries later in the study area, due to the deglacial lag between the outer coast of the island and the study area (Dallimore et al., 2008).

**Paleoenvironments**

Pollen analysis by Pellatt et al. (2001) from marine sediment cores in nearby Saanich Inlet indicates that vegetation has likely changed quite rapidly in the study area throughout the Holocene epoch and this would indicate definitive changes in climate post glaciation. The climate in B.C. was cool and dry towards the end of the last glaciation and following that, there was a period of warming (about 5°C) over a century or two (Hebda, 1995; Lemmen et al., 2008; Walker & Pellatt, 2003). Following this, there were three intervals: warm and dry from 10,000 to 7,400 YBP; warm and moist from 7,400 to 4,400 YBP and cooler (close to modern) from approximately 4,400 years ago (Lemmen et al., 2008). Table 1 and Figure 7 summarize the changes in climate and vegetation assemblages around southern Vancouver Island during the past 15,000 years. One note from Table 1 is that from 10,350 to 8,300, the assemblage indicates landscape may have been regularly disturbed, likely by fire (Mathewes, 1985 as cited in Pellatt et al. 2001).

<table>
<thead>
<tr>
<th>Time period (YBP)</th>
<th>Vegetation Regime</th>
<th>Climatic conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>3800 - 1050</td>
<td>Alder (<em>Alnus</em>), cedar (<em>Cupressaceae</em>), western hemlock (<em>Tsuga heterophylla</em>), spruce (<em>Picea</em>)</td>
<td>Mild/moist climate indicative of modern neoglacial conditions established.</td>
</tr>
<tr>
<td>5750 – 3800</td>
<td>Alder, cedar, western hemlock</td>
<td>Period of climatic transition from early Holocene warm/dry conditions to a mild/wet neoglacial</td>
</tr>
<tr>
<td>7040 – 5750</td>
<td>Oak (<em>Quercus</em>), Douglas fir (<em>Pseudotsuga</em>), western hemlock</td>
<td>Cool and/or wetter; mixed conifer/hardwood parkland or woodland</td>
</tr>
<tr>
<td>8300 – 7040</td>
<td>Oak, true grasses (<em>Poaceae</em>), alder, ferns (<em>Pteridium</em>)</td>
<td>Warmer and drier than present but not as dry as 11450 - 10350</td>
</tr>
<tr>
<td>10350 – 8300</td>
<td>True grasses, ferns, alder, Douglas fir</td>
<td>Warmer and dryer than recent; parkland</td>
</tr>
<tr>
<td>11450 – 10350</td>
<td>True grasses, ferns, pine (<em>Pinus</em>), alder, Sitka spruce (<em>Picea sitchensis</em>), lodgepole pine (<em>P. contorta</em>), and alder</td>
<td>Relatively mild temperatures; open landscape, perhaps parkland in nature</td>
</tr>
</tbody>
</table>
Figure 7. Sea level change and corresponding changes in vegetation assemblages from Yorath, Kung, & Franklin (2002). The red star indicates the location of the clam garden case study sites in GINPR. The time slices move from immediately post glacial at 14,500 years before present, and through 6,000 years before present when sea level stabilized to be close to present day levels. The images show the changes in ice cover, vegetative assemblage and sea level. Changes in vegetation can occur relatively quickly and likely indicate a change in climate as glacial ice leaves the area, and present day seasonality is established.

Clam Gardens

Humans have been modifying ecosystems for thousands of years. Along the coast of British Columbia and Alaska, structures called clam gardens or walled gardens have recently been re-discovered and they are thought to have been constructed throughout the late Holocene (Deur et al., 2015; Groesbeck et al., 2014; Lepofsky et al., 2015; Moss, 2011). These walls are one of a number of examples of intertidal features found in the archaeological record along the coast of B.C. (Caldwell et al., 2012). The existence and detailed knowledge of the construction, maintenance and harvesting of clam gardens have
been known by coastal First Nations likely for several thousand years. Clam gardens are one example of managed habitats and indigenous resource management systems (Deur et al., 2015). The Kwakwaka’wakw Nation refer to the clam gardens as loxiwey (plural lokiwey), which means “to roll” and this relates to “rolling of rocks out of clam beds and into the lower intertidal zone, a primary activity of their creation and maintenance” (Deur et al., 2015, p. 202). Kwakwaka’wakw incorporated clams and lokiwey into their cultural practices, including songs and stories (Deur et al., 2015). This would indicate that they have been important for many generations. An elder indicates that oral tradition says “(p)eople have been doing this, building their lokiwey, since the beginning of time. There are some maybe 2,000 years old on the coast” (Deur et al., 2015, p. 206). In addition to being a valuable food source, the clams were also a commodity, being traded for other goods as needed (Deur et al., 2015).

The Ahousaht dialect of Nuu-chah-nulth used the term t’iimik (“move aside rocks” or “something being thrown”) to label an especially good beach in Clayoquot Sound that was known to be a location where clams were cultivated (Bouchard & Kennedy, 1990, as cited in Lepofsky et al., 2015). The Tla’amin, speakers of Mainland Comox, referred to structure of rocks piled at the sides of the beach or at the low water mark to during clam digging to make future digging easier, as wuxwuthin (“held back at the mouth”) (Bouchard & Kennedy, 1974, as cited in Lepofsky et al., 2015).

The gardens consist of human created rock walls, parallel to the coastline at the mouths and along the edges of embayments, and they stabilize sediments at a specific tidal height (Groesbeck et al., 2014). Evidence of anthropogenic intertidal rock terraces, thought to be built throughout the Holocene, have been recorded in from southern
Vancouver Island in British Columbia to Baranof Island, on which Sitka, Alaska is located (Harper, 2012 as cited in Augustine & Dearden, 2014). The tendency is for clam gardens to be located in places well flushed by tidal currents and not in protected areas with fresh water sources, such as streams or a freshwater estuary (Lepofsky et al., 2015). Figure 8 shows a diagram of the clam garden terrace cross-section. Field studies indicate the rock walls were built at specific tidal heights in order to maximize optimal clam habitat (Groesbeck et al., 2014; Harper et al., 1995). One study area on Quadra Island had four times the number of butter clams and twice as many littleneck clams relative to non-walled beaches (Groesbeck et al., 2014). Lepofsky et al. (2015) found instances where new clam habitats were created, where none had previously existed, through the creation of a rock wall for a clam garden.

While the general structure of clam gardens observed along the B.C. coast is similar, there is notable variation in the cultural and ecological contexts of these features, with some being built over a short time and others over an extended period of time (Lepofsky et al., 2015). The purpose of these walls is presumed to be enhanced shellfish productivity. Traditional ecological knowledge (TEK) indicates the clam beds were sustainably harvested, with larger clams being harvested and smaller ones left to grow (Deur et al., 2015). It is known that clams grow better if their habitat is periodically disturbed and populations thinned and the aforementioned selective harvesting would serve this purpose (Deur et al., 2015). In addition to the selective harvesting, TEK states that harvesting was only done during the lowest tides in the winter months, which occurred in the middle of the night. Tending the gardens was done during the lowest low tides in early summer, which occurred during the day. Winter months and early summer
Sea Level Change in the Gulf Islands National Park Reserve

were times when the danger of toxic algal blooms was minimal.

One recent experiment has shown clam garden may have better water retention when compared to natural sloping, non-walled beaches (Groesbeck et al., 2014). It is hypothesized that this increased water retention may increase larval recruitment and survivorship as well as enhancing growth rates (Groesbeck et al., 2014). Other insights have been reported in an important and unique recent paper which contains both modern scientific inquiry and TEK from Coast Salish elders (Deur et al., 2015). Important insights from this research include indications that as long as the beds were kept clean and maintained and as long as the harvesting rates did not exceed the reproductive capacity and in a season that did not impair the reproductive capability, the clams would continue to regenerate. Examination and carbon dating of one of the beds by Groesbeck et al., (2014) suggests that shellfish were a staple food source for Northwest Coast First Nations for at least 5000 years (Cannon, Burchell, & Bathurst, 2008).

Figure 8. Cross section of clam garden structure as compared to a non-walled beach. The volume of available habitat is increased with the rock wall. Diagram adapted from Groesbeck et al. (2014) Figure 3.

Influences of Global Climate Change

Predicted future increases in sea level along the B.C. coast due to global climate change have potentially negative impacts on coastal and low lying regions in British

---

Columbia (Lemmen et al., 2008) and around the world (Church et al., 2013). Evidence from the IPCC shows that it is likely that the rate of global mean sea level rise has continued to go up since early in the 20th century, with upper estimates being approximately 0.013 mm yr\(^{-2}\) (Church et al., 2013). Tide gauge records and satellite data show that global sea level has risen by more than 20 cm since the late 19th century (Bornhold, 2008). Changes in sea level during the 20th century in B.C. have been quite variable (Lemmen et al., 2008). Sea level rose eight centimetres in Victoria, four centimetres in Vancouver and 12 centimetres in Prince Rupert while dropping 13 centimetres in Tofino (British Columbia Ministry of Water, Land and Air Protection, 2015). There is uplift happening on the coast, likely due to strain accumulation in the CSZ, and this is likely the reason for sea level drop in Tofino (Verdonck, 2006).

According to the IPCC (Church et al., 2013), evidence currently available suggests that if global warming continues above a certain threshold greater than pre-industrial, there would be a near-complete loss of the Greenland ice sheet over the span of 1,000 years or more and this would lead to a rise in global sea level of approximately seven metres. This would be due to glacial melt water as well as tectonic processes. Temperature changes significantly contribute, through thermal expansion or contraction, to global average ocean volume (Gregory & Lowe, 2000 as cited in Church et al., 2013). In addition, the height of potentially damaging significant high water events along the B.C. coast due to increasing severity of storms creating sea surges, is increasing at a rate greater than the rate of sea level rise (Lemmen et al., 2008).

Impacts of climate change that lead to global sea level rise include thermal expansion due to warming ocean water, local shifts due to vertical land motion, and melt
water from glaciers, ice caps, and ice sheets in Greenland and Antarctica (Bornhold, 2008). The dominant contributors to 20th century global mean sea level rise have been ocean thermal expansion and glacier melting (Church et al., 2013). Changes in ocean volume due to heating of surface waters results in approximately 1.6 mm per year in global sea level rise. Melting glaciers in Antarctica, Greenland and mountain areas account for a rise of about 1.2-1.6 mm per year (Bornhold, 2008). Resulting impacts that may occur on short time scales include erosion, inundation, and coastal flooding which arise from severe storm induced surges, wave overtopping, and rainfall runoff (Barnard et al., 2015; Wong et al., 2014). Longer term impacts may include alteration of wind and wave patterns which, in turn, may cause changes in coastal sediment transport and sediment erosion and accretion.

**Future Sea Levels**

Predictions exist for the amount of expected future global sea level change from General Circulation Models (GCM) and various imagined scenarios of future global emissions, which are based on visioning of a range of global socio-economic pathways. For example, three IPCC scenarios are outlined for various time periods in Table 2. The IPCC’s GCM models used to generate the predictions of future sea level rise, incorporate estimates for thermal expansion of the ocean, glacial melt, Greenland Ice Sheet melt and Antarctic Ice Sheet melt. There is a spread in the predicted values as four different types of models used: process based models, semi-empirical models, models that use of paleo-sea level records and models that focus on ice-sheet dynamics (Church et al., 2013). The predictions up to 2100 are of higher confidence than those beyond 2100. However, the ice sheets and ocean temperatures will continue to respond to external forces and
therefore sea level will continue to change (Church et al., 2013). In addition, regional changes will likely vary significantly from the global average. This is due to localized ocean processes, sea floor movement and gravity changes due to water mass redistribution. The timing for all of these processes is different as is the relative contribution of each so it is difficult to accurately predict localized changes (Church et al., 2013). Regardless, impacts of sea level rise in British Columbia will likely be significant. For example, if sea level rose one metre all along the coast, more than 4,600 hectares of farmland and 15,000 hectares of industrial and residential urban areas would be flooded (Yin, 2001).

Table 2. Model spread of global sea level change for low, medium and high greenhouse gas emissions scenarios (values extracted from Table 13.8 from Church et al., 2013). The predictions take into account thermal expansion, glaciers, the Greenland ice sheet and the Antarctic ice sheet. All predictions are in metres [m].

<table>
<thead>
<tr>
<th>Scenario</th>
<th>2100</th>
<th>2200</th>
<th>2300</th>
<th>2400</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0.26 – 0.53</td>
<td>0.35 – 0.72</td>
<td>0.41 – 0.85</td>
<td>0.46 – 0.94</td>
<td>0.50 – 1.02</td>
</tr>
<tr>
<td>Medium</td>
<td>0.19 – 0.66</td>
<td>0.26 – 1.09</td>
<td>0.27 – 1.51</td>
<td>0.21 – 1.90</td>
<td>0.18 – 2.32</td>
</tr>
<tr>
<td>High</td>
<td>0.21 – 0.83</td>
<td>0.58 – 2.03</td>
<td>0.92 – 3.59</td>
<td>1.20 – 5.17</td>
<td>1.51 – 6.63</td>
</tr>
</tbody>
</table>

**Projected sea levels along the B.C. Coast**

In regards to the British Columbia coast, future changes in sea level will not be uniform, with some regions experiencing a more significant rise (Lemmen et al., 2008). Table 3 outlines projected sea level changes for various locations in B.C. These predictions are derived from historical sea level trends using tide gauge data (Bornhold, 2008). Similarly, evidence for this non-uniform regional paleo-sea level change along the B.C. coast has been reported in various studies related to paleo environments, marine geology and archaeology (Clague & James, 2002; Dallimore et al., 2008; Grier et al., 2009; Hutchinson, James, Clague, Barrie, & Conway, 2004; James et al., 2009; Mackie et
Table 3. Relative sea level rise by 2100 for selection locations in British Columbia (adapted from Table 1 from Bornhold, 2008). These values were derived from historical tide gauge data.

<table>
<thead>
<tr>
<th>Location</th>
<th>Sea Level Rise based on extreme low estimate of global sea level rise [m]</th>
<th>Sea Level Rise based on mean estimate of global sea level rise [m]</th>
<th>Sea Level Rise based on extreme high estimate of global sea level rise [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prince Rupert</td>
<td>0.10 – 0.31</td>
<td>0.25-0.46</td>
<td>0.95-1.16</td>
</tr>
<tr>
<td>Nanaimo</td>
<td>-0.04</td>
<td>0.11</td>
<td>0.80</td>
</tr>
<tr>
<td>Victoria</td>
<td>0.02 - 0.04</td>
<td>0.17 – 0.19</td>
<td>0.89 – 0.94</td>
</tr>
<tr>
<td>Vancouver</td>
<td>0.04 – 0.18</td>
<td>0.20 – 0.33</td>
<td>0.89 – 1.03</td>
</tr>
<tr>
<td>Fraser River Delta</td>
<td>0.35</td>
<td>0.50</td>
<td>1.20</td>
</tr>
</tbody>
</table>

**Influence of Anthropogenic Activities**

There are also anthropogenic activities that may influence future sea level. These include reduced sediment delivery to the coast, sediment consolidation from building loads, and extraction of subsurface resources (Wong et al., 2014). Climate is naturally variable but these anthropogenic activities may influence this natural variability through changes in the behaviour of storms, winds and waves. Coastal marine species may also undergo changes in regard to habitat, biodiversity and population due to changes in water temperature and ocean acidity. Additional impacts may include changes in fresh water supply, increased pressures on fisheries and agriculture and increases stresses on forests from fires and pests (Lemmen et al., 2008).

**Tectonic Influences**

Tectonic influences vary in this region due to the increasing strain in geologic time along the CSZ (Figure 6), with some portions of the coast being tectonically uplifted while other portions are lowered (Bornhold, 2008). In regards to crustal uplift due to vertical strain accumulating along the CSZ, it “is not expected to significantly ameliorate projected sea-level rise in the mid and northern Strait of Georgia because present-day vertical crustal movements are inferred to be small.” (James et al., 2005, p. 113).
Other natural crustal subsidence will impact sea levels in B.C. For example, it is expected that subsidence of the Fraser River Delta will be on-going due to the sediment loading from the Fraser River, and this will accelerate relative sea level rise in the Vancouver and Richmond (Mazzotti, Lambert, Van der Kooij, & Mainville, 2009).
Methods

Sea Level Mapping

ArcMap (ArcGIS 10.2.2) was used to create models of the coast landscape under a variety of sea level conditions. The paleo-sea level values and predicted future sea level estimates were synthesized from the literature (Table 4 and Table 5). The data used to create the modelled paleo-sea level curved for GINPR were acquired from Church et al. (2013); James et al., (2009), Mosher & Hewitt (2004) and (Thomson et al., 2008) and the appropriate references are noted in the table. Topography and bathymetry data were provided by Natural Resources of Canada (NRCan) spatial database.

The bathymetric and topographic raster data were brought into ArcMap as layers from the NRCan spatial data (R. Kung, 2015, pers. comm.). The bathymetric data exists as a geodatabase of multibeam bathymetry and hill-shaded relief. The topography exists as a digital elevation model (DEM) and hill-shaded relief file. These data had previously processed in order to put them into the ArcGIS format. The following steps were followed:

1. The data boundaries were larger than needed for this study, so the area of interest was isolated and each of the above data sets were exported to new layer.

2. The topography resolution was 30 metres square so re-sampling was necessary to match the resolution of the bathymetry, which is 5 metres square. The Resample tool was used with a Nearest Neighbour interpolation being applied. The same method was applied to the hill-shaded relief layers.

3. The topography and bathymetry layers, as well as the relief layers, were merged together to create one continuous layer using the Mosaic to New Raster Tool.
4. Gaps remained between the bathymetry and topography so an attempt to remove them was done using the Focal Statistics tool. The gaps are due to the areas not being mapped (i.e. no data is available). The purpose of this tool is to interpolate the gaps and create a continuous layer. It was a challenge to reduce the gaps without having a significant impact on the data accuracy for this particular data set. It was decided, in the interest of maintaining resolution and accuracy, that the interpolation would not be performed. This is addressed further in the Discussion section.

5. To create each different map, the colour ramp was adjusted in the Symbology tab of the Layer Properties, to indicate paleo and future sea levels. Red was always used to indicate the highest extent of sea level. The hill-shaded relief was adjusted to 60% transparency in the Display tab of the Layer Properties in order for the colours to shine through the lower layers.

**Isolation Basin**

Isolation basins provide valuable physical evidence to determine where sea level was at a specific moment in time, in a local area. This transition indicates the precise time that sea level fell locally (i.e. from grey marine clays to terrestrial peat and/or lake sediments above). If this sedimentary transition can be found, and dateable organic material is present, then the paleo-sea level can be accurately determined for a specific local area (Dallimore et al., 2008; Hutchinson et al., 2004; James et al., 2005; James et al., 2009). In “coastal British Columbia, a typical isolation basin is a lake, marsh, or bog located below the limit of glaciomarine inundation” (James et al., 2005, p. 114). Isolation basins are a common method of developing local sea level curves, but appropriate coring
locations are quite difficult in practice to locate (A. Dallimore, 2015, pers. comm.). For this study, satellite imagery of Saltspring Island was examined for any lakes or ponds present near Fulford Harbour as potential isolation basins that could be cored and examined for the presence of the marine/terrestrial interface. Coring was not performed due to time constraints.
Results

Paleo-sea Levels

Sea level curves for different parts of the British Columbia coast, and the global (eustatic) sea level data published by Stanford et al., (2006), were compiled into one graph (Figure 9). The reference literature for each sea level curve is shown in the legend box of the figure. The variability between some of the curves is quite noticeable and is a result of the aforementioned factors outlined in the literature review, such as variable timing of ice retreat in local areas and differences in mantle viscosity, which decreased from north to south along the B.C. coast. Note a spread of about 100 meters early in deglaciation, with the most change in Hecate Strait. Glacial isostatic rebound was uneven across the coast and does not decline in a smooth manner from the peak values. All the referenced studies agree that glacio-isostatic rebound ceases between about 6,000 and 4,000 years along the coast, with Hecate Strait lagging somewhat behind the rest of the coast in re-establishing equilibrium post-glaciation. This end to glacio-isostatic rebound is evident in the graph by the levelling-off of all the curves starting at about 6,000 years before present. It is worth noting, however, that there is minimal data for the past 5,000 years. There is archaeological data from Fedje et al. (2009) that provides some points on the graph within this time frame. The convergence of multiple sea level curves indicates this lack of data, in addition to the probable lack of significant dynamics in recent sea level history (I. McKechnie, 2015, pers. comm.).
A series of GIS modelled time slice paleo-sea level maps were created to represent the paleo-sea level time slices in the region of the clam gardens case study sites in GINPR. There was no interpolation done on the bathymetry and topography on the maps after those two layers were merged, so the white gaps present on the maps is where there is no topographic or bathymetric data. The reason that interpolation was not performed is the desire to avoid any data or accuracy loss or rounding errors that happens when interpolation is performed. Interpolation can introduce biases since there is little actual data in the nearshore, intertidal areas (I. McKechnie, 2015, pers. comm.). To approximate full coverage, gaps were coloured in for a subset of the maps and these are
shown in Appendix A. The topographic layer is left as grey scale in order the shorelines are distinctly highlighted. The highest elevations are dark and the lowest values, closest to sea level, are the lighter colours. Table 4 and the figures that follow show present day sea level and six paleo time slices: 5,000, 8,000, 9,079, 9,849, 11,750 and 12,200. These specific time slices were chosen, in roughly thousand year intervals, from the best available data in the proximity of the clam garden case study sites. Sea levels are quite high immediately after glaciation. Then, as isostatic rebound continues and the land rises, sea levels drop significantly. As glacio-isostatic rebound ceases and crustal equilibrium is achieved, sea level stays relatively stable since approximately 6,000 years BP along the B.C. coast. Noticeable on this and the subsequent figures is a submarine trough, represented in light green to blue trending across the map from the northeast to the southwest. This may be the result of bottom current circulation due to coastal ocean currents (Thomson, 1981). Barrie & Conway (2002) have identified these features as current eroded bottom troughs elsewhere on the B.C. coast from multibeam data.
Table 4. Paleo-sea level values from south-eastern Vancouver Island paleo-sea level literature. Values are relative to current sea level (RSL). The value for 3,500 provides recent data from within GINPR (Fedje et al., 2009). The values from James et al., (2009) are the most recent and closest in proximity to the study area. The values from Mosher & Hewitt (2004) are from an earlier study and slightly further away (eastern Juan de Fuca Strait) but provide values to fill in the time gaps near 9,000 and 10,000 YBP. Values that were taken from samples are referenced and include ± errors. Values taken from the publication’s text do not have error values.

<table>
<thead>
<tr>
<th>Time [^{14}C YBP]</th>
<th>RSL [m]</th>
<th>Source</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present day</td>
<td>0</td>
<td>n/a</td>
<td>Figure 10</td>
</tr>
<tr>
<td>3,500 ± 15</td>
<td>-1.25</td>
<td>Fedje et al., (2009, p. 244, ref. 1659T2-145)</td>
<td>Figure 11</td>
</tr>
<tr>
<td>5,000</td>
<td>-4</td>
<td>James et al., (2009, p. 1207)</td>
<td>Figure 12</td>
</tr>
<tr>
<td>8,000</td>
<td>-30</td>
<td>James et al., (2009, p.1213 and Figures 9a and 12)</td>
<td>Figure 13</td>
</tr>
<tr>
<td>9,079 ± 50</td>
<td>-44</td>
<td>Mosher &amp; Hewitt (2004, p. 34, ref. CAMS58685)</td>
<td>Figure 14</td>
</tr>
<tr>
<td>9,849 ± 230</td>
<td>-55</td>
<td>Mosher &amp; Hewitt (2004, p. 34, ref. RIDDL-258)</td>
<td>Figure 15</td>
</tr>
<tr>
<td>11,750 ± 110</td>
<td>+30</td>
<td>James et al., (2009, p. 1203, ref. SFU-549, and p.1207)</td>
<td>Figure 16</td>
</tr>
<tr>
<td>12,200</td>
<td>+75</td>
<td>James et al., (2009, p. 1209 and Figure 12)</td>
<td>Figure 17</td>
</tr>
</tbody>
</table>

Figure 10. Present day sea level. The black and white areas represent topography above the waterline. The case study sites are marked by the yellow and red stars. White areas indicate a lack of data in intertidal zone.
Figure 11. Sea level 3,500 years before present when glacio-isostatic rebound had likely ceased in the GINPR area, 1.25 metres below current levels. This indicates that, if clam gardens were in use at the time, there may be evidence of them now submerged below current sea levels. Climatic conditions were similar to present day. White areas indicate a lack of data in intertidal zone.

Figure 12. Sea level 5,000 years before present when glacio-isostatic rebound had likely ceased in the GINPR area, 4 metres below current levels. Climatic conditions were similar to present day.
Figure 13. Sea level 8,000 years before present, at 30 metres below current levels. This time slice represents deglaciation when sea levels were much lower than today’s due to sea water frozen into waning glaciers and ice sheets, and the crust exhibited depression due to the weight of the recently melted ice sheets. Climatic conditions were warmer and drier than present.

Figure 14. Sea level 9,079 years before present, 44 metres below current levels. There may be archaeological evidence for clam gardens along these now submerged shorelines. There is evidence for the Salish Sea, including the nearby San Juan Islands, being populated during this time (Kenady, Wilson, Schalk, & Mierendorf, 2011; Waters et al., 2011). Climatic conditions were warmer and drier than present day.
Figure 15. Sea level 9,850 years before present, 55 metres below current levels. Between this time and the sea level highstand in Figure 17, the crust rebounded from glacio-isostatic depression immediately post-glaciation.

Figure 16. Sea level 11,750 years before present, 30 metres above current levels. At this time, the crust would have been severely depressed from the weight of glacial ice, allowing inundation of the sea into the area. Examining the location of these shorelines could provide more archaeological evidence for clam gardens. Climatic conditions would be warmer and much drier than present day.
Sea Level Change in the Gulf Islands National Park Reserve

Figure 17. Sea level 12,200 years before present, 75 metres above current levels. At this point in time, many of the islands surrounding Saltspring Island were submerged, including Russell Island. In addition, it shows that the current area known as Saltspring Island was once at least three islands.

Isolation Basins

Utilizing satellite imagery from ArcGIS, several small bodies of water near Fulford Harbour on Saltspring Island were identified as potential isolation basins. These are indicated on the map in Figure 18. The time constraints of this thesis did not allow for acquisition of permits and coring. If coring were to take place, a marine terrestrial transition found in the sediments and the transition could be dated using radiocarbon dating methods, a specific sea level data point for the case study area could then be added to Figure 9.
Clam Gardens

Clams gardens have been increasingly documented in the archaeological literature in recent years. Several clam garden sites along the British Columbia and Alaska coast have been located (Figure 19). Some of these sites are from formal published literature and others are from unpublished reports. Parks Canada researchers, in partnership with Coast Salish First Nations, are undertaking the restoration of two clam gardens in Gulf Islands National Park Reserve. These restorations will take place over approximately five years and began in 2015. Objectives of this research include improving the conditions of the gardens, examining the role of clam gardens in restoring intertidal ecosystems,
developing recommendations for traditional and scientific management techniques and reconnecting First Nations to cultural landscapes (Cardinal, 2014).

Two known clam gardens were visited during the course of this research. Both of them are part of the Parks Canada restoration program in GINPR. One was along the shoreline of Fulford Harbour on Saltspring Island. The precise location is indicated in Figure 5. Figure 20 shows a photograph of the clam garden itself. The boulders in the foreground are where the wall is and the light green marine vegetation is covering the clam beds. The other location is Russell Island, located just at the edge of the mouth of Fulford Harbour (Figure 5 and Figure 21). Figure 22 shows the rock wall for the clam garden just submerged under water.

The modelled time slice paleo-sea level maps from the previous section show how significant the environment changes have been in the past. The age of the clam garden sites in GINPR is not presently known nor do we know how long they were in use for. It is unknown how long these clam gardens have been used by First Nations groups, but there is evidence for human habitation in each major section of the Pacific Coast of North America as far back as 13,500 to 11,000 calendar years ago (Erlandson, Moss, & Deslauriers, 2008). First Nations communities are known to have inhabited this region of the Salish Sea during the times in question (Kenady et al., 2011; Kopperl, Taylor, Ames, & Hodges, 2015; Waters et al., 2011) and therefore, evidence of further clam gardens may be present along the well flushed tidal areas of paleo coastlines shown in the maps.
Figure 19. Locations of clam gardens currently mapped in the literature. Literature sources for these sites are Harper (2012) as cited in Augustine & Dearden (2014); Cardinal (2014); Fedje & Smith (2010); Harper et al. (1995); Lepofsky et al., (2015). Base map copyright © Esri.

Current Sea Levels at Fulford Harbour and Russell Island

When visiting the Fulford Harbour and Russell Island at low tide on June 15, 2015, an interesting observation was made. The Fulford site was visited first and the wall was quite noticeable above the water line (Figure 20). The Russell Island site was visited next, approximately 15 minutes later, and the wall was only slightly visible above the water (Figure 21). The Russell Island site restoration has begun and boulders have been added to this wall so the original level (when it was first discovered) was even lower
below sea level than in the photo. This corresponds with observations that the Russell Island site boulder wall can only be seen fully at 0.3 m tides, whereas the Fulford site can be seen at 0.5 and even 0.6 m tides (A. Dallimore, 2015, pers. comm.). This indicates that the two sites may have been built at different sea levels and therefore are not the same age, despite their proximity.

Figure 20. Rock wall for clam garden in Fulford Harbour on Saltspring Island, British Columbia, looking south to the Saanich Peninsula across Satellite Channel, June 15, 2015 (Figure 18).
Figure 21. The Russell Island clam garden site looking to the south, onto the north shore of Russell Island. The rock wall is just visible above the waterline in the foreground of the photo. Note this photo was taken within 15 minutes of the photo in Figure 20, showing the noticeable difference in wall height, which may suggest that the Russell Island site was built at an earlier time, during a lower sea level stand than at the construction time of the Fulford Harbour site.

Figure 22. Rock wall for clam garden on Russell Island, B.C. The white line indicates the submerged wall, which was under water at the same time as the wall at Fulford Harbour was exposed on June 15, 2015.
Future Sea Levels

Using the same methodology used to create the modelled time slice paleo-sea level maps, GIS maps were created for predictions of future sea level. The same notes as the paleo maps apply here in regards to interpolation (see page 37). Table 5 outlines the years with the predicted sea levels for three time slices, the literature source and the figure number. The value for 2100 is based on historic tide gauge data. The value for 2300 is from processed-based atmosphere-ocean GCM models which try to incorporate earth processes and interactions. The value for 2500 is based on a semi-empirical models (SEMs), which do not attempt to simulate earth processes. SEMs use statistical relationships between observed global mean sea level and global mean temperature to project sea level and usually result in higher predictions than the process-based models (Church et al., 2013). However, elements of SEMs are sometimes incorporated into the process-based models.

Table 5. Predictions for sea level rise. Values are relative to current sea level. The 2100 value is the highest value for Victoria from Table 3. The 2300 and 2500 are global predictions and therefore are only a wide approximation for the region of GINPR. The value for 2500 is the highest value from a semi-empirical model run by Jevrejeva et al. (2012a) (as cited in Church et al., 2013).

<table>
<thead>
<tr>
<th>Date</th>
<th>RSL [m]</th>
<th>Source</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100</td>
<td>0.90</td>
<td>(Thomson et al., 2008)</td>
<td>Figure 22</td>
</tr>
<tr>
<td>2300</td>
<td>3.59</td>
<td>Church et al. (2013)</td>
<td>Figure 23</td>
</tr>
<tr>
<td>2500</td>
<td>11.5</td>
<td>Church et al. (2013)</td>
<td>Figure 24</td>
</tr>
</tbody>
</table>

The maps below show a gradual but substantial rise in sea level over the next 400 years. Due to the large scale, they are not as visually striking as the previous maps showing sea level several tens of metres above present but they do indicate where the first points of inundation will be along the coastline of the study area. It is important to note that a one metre sea level rise in 100 years is approximately the same rate as when the earth was going through deglaciation. In order for glaciers to melt and retreat, the
temperatures must be very warm. This shows the significant power of human forcing mechanisms in the earth system due to global climate change (Steffen et al., 2005).

Figure 23. Sea level prediction for 2100, 0.94 metres above current sea level. While not visually striking, the small red areas along the coast line show where the first areas of sea level inundation will be.
Figure 24. Sea level prediction for 2300, 3.6 metres above current sea level. Focusing on Russell Island, it can be seen that several parts of the shore line would be submerged at this level.

Figure 25. Sea level prediction of 11.5 metres of sea level for the year 2500. This is the highest sea level prediction made by the IPCC (Church et al., 2013). The highest high value is used to emphasize the significant impact sea level change will have on B.C. coastal communities in the next 400 years due to global climate change. This shows a significant inundation of water at the upper end of Fulford Harbour and this would have an impact on the current community surrounding the harbour. In addition, Russell Island has become three islets.
Discussion

Paleo-sea Levels

Sea level curves for the British Columbia coast reported in the literature vary significantly, due to factors such as variable timing of ice retreat in local areas, tectonics, coastal erosion and differences in mantle viscosity, as shown in Figure 9. The curves were derived from a variety of physical information, the most common of which is isolation basins. Isolation basins with a marine/terrestrial boundary and datable organic material give a reliable time frame for the sea level at a particular point in time at a specific location. Archaeological data can also be a useful tool in this regard. Estimates of the likely minimum sea level can be derived from archaeological site deposits (Fedje et al., 2009). Further investigation in the current and paleo intertidal zones may yield more archaeological evidence for sea level change (Fedje et al., 2009). As more data is accumulated for a specific area, there is the potential for the paleo-sea level curves to become more refined and accurate. However, this assumes that more recent studies have better data and improved methodology and this is not always the case.

Figure 7 and Table 1 indicate that the air temperatures in the study area were quite warm immediately following deglaciation. This would make sense as atmospheric temperatures would need warm up substantially to initiate a glaciation (Steffen et al., 2005). As deglaciation progressed, the climate began to equilibrate and seasonality likely re-established within a few centuries after the ice left the area. This was observed to be the case from a marine sediment core in Effingham Inlet on the outer coast of Vancouver Island (Dallimore et al., 2008). This climatic equilibration likely included the return of seasonality, the cooling of air temperatures and the recreation of world-wide ocean
Sea Level Change in the Gulf Islands National Park Reserve

circulation (Steffen et al., 2005). Approximately 6,000 years ago, glacial isostatic rebound along the outer south coast of B.C. was complete (Figure 9 and Dallimore et al., 2008). The climate has also remained relatively stable since then. It can be presumed that coastal ocean dynamics became established around Vancouver Island, and likely also the study area, in the early stages of deglaciation (Dallimore et al., 2008; Tunnicliffe, O’Connell, & McQuoid, 2001).

Following the end of isostatic rebound in the study area, co-seismic subsidence likely occurred and caused sudden rises in sea levels of several metres concurrent with megathrust earthquakes, which are thought to have occurred about every 500 to 1,000 years along the CSZ (Enkin et al., 2014) with the last one occurring on Jan, 21, 1700 AD (Clague & Bobrowsky, 1994).

The modelled time slice paleo-sea level maps presented in the results show how dramatically sea level has changed at the clam garden case study sites since de-glacial times. The shorelines that are drastically higher than the present day coastline show how low lying terrestrial features can disappear under the water, including entire islands. Sea levels lower than present show the potential possibility for submerged archaeological features (Mackie, Davis, Fedje, McLaren, & Gusick, 2014). The future shore line models with rising sea levels due to global climate change, illustrate sea level changes in the order of post-glacial times, but occurring over centuries, instead of millennia.

Any discussion on paleo dates involves radio-carbon dating. The geological and archaeological literature explains the many subtleties of effective radio-carbon dating and interpretation. This is due to the number of dates, samples used, and uncertainties reported and the reporting method. All these variables can make it difficult to compare
$^{14}$C dates reported from various regional studies. However, with reasonable care, age trends can be discerned while comparing $^{14}$C dates reported in regional studies (for example Figure 9 and Table 4) (Telford, Heegaard, & Birks, 2004).

**Clam Gardens**

The map of the clam garden locations, from research to date, along the coast of British Columbia and Alaska shows a very large north-south extent of these features (Figure 2). Researchers now know that clam gardens are located all along the coast (Deur et al., 2015). There may be TEK of clam garden locations among the First Nations groups along the coast but they may only be held in oral tradition and never written down. Many First Nations communities along the coast are beginning to make inventories of the clam gardens in their territories (J. R. Harper, 2015, pers. comm.). These sites may then be put on official record with the Archaeology Branch of the British Columbia Ministry of Forests, Lands and Natural Resource Operations (N. Smith, 2015, pers. comm.). The general public, exploring up and down the coast, may have come across these features and may not have known what they were or documented the location.

Even though the case study GINPR clam gardens are not resolved on the modelled time slice paleo-sea level maps, they do show that a small change in sea level would have had, and in the future will have, a significant impact on the clam gardens. This is due to their location in the intertidal zone. It is uncertain whether or not, in the past, the walls of the clam gardens were raised or lowered corresponding to changes in sea level or, if the gardens were abandoned and a different, suitable location was found. It can be inferred from the field observations that the Russell Island site may be older than the Fulford site. The Russell Island site was examined and the oldest organic material
found was dated at 1208 to 1043 calibrated years before present (Deur et al., 2015). If clam gardens were being built when sea level was above current levels, then there may be paleo clam garden sites above and inland from the current shoreline. Some of these for example, are indeed exposed today, located high and dry above the current high tide line on Quadra Island in Georgia Strait, where paleo-sea level had a complex history (N. Smith, 2015, pers. comm.). In addition, there may be older clam gardens submerged under the water as sea level has also been much lower than present if they were built at a low sea level stand.

The nearshore intertidal zone, where clam gardens and other important archaeological and geomorphological features are found, is a challenging one from a mapping perspective. The topographic data used here was subsampled down from 30 metres to 5 metres. This results in some loss in accuracy with a gain in assumed precision. This is starkly displayed in the “white zone” present in the sea level maps presented in the results section. In addition to there being a general shortage of data, it data that exists is from two different mapping disciplines, that of topography and bathymetry. There are differences in agencies responsible for the data, data acquisition, resolution, vertical datums and standards for defining and representing features (Bartier & Sloan, 2007). All of these factors must be kept in mind when attempting to map this area. In regards to data acquisition, the intertidal zone is a challenge as acquisition can only be done during high tide and sonar bathymetric systems do not always function well in extremely shallow water (Bartier & Sloan, 2007). One solution that is being used now is LIDAR (light detection and ranging) technology, which is capable of acquiring data in the terrestrial realm and up to 50 metres (in clear water) water depth (Klemas, 2011). The
same considerations - datum, resolution and standards, must also be taken into account when integrating this data with the topology and bathymetry.

As clam gardens are located and restoration is undertaken, changing sea level should be taken into account and mitigated for during restoration. Paleo-sea level curves may also help to infer the age, or relative age of clam gardens as described in the results for the case study sites in GINPR. The predicted rising sea levels along the B.C. coast due to climate change is not the only potential event that would impact the clam gardens. It is known that a subduction zone earthquake occurred on the west coast of Canada on January 21, 1700 AD (Clague & Bobrowsky, 1994). A phenomenon referred to as coseismic subsidence occurred during this earthquake and the land subsided, possibly as much as four metres, very quickly as a result of the earthquake. Potential evidence of another significant earthquake and coseismic subsidence, within twenty kilometres of the study site, is a drowned forest (Figure 26), with tree roots dating to 2,040 years old, found on Island View beach on the east coast of Vancouver Island (Yorath, 2005). Evidence found in marine sedimentary data from Effingham Inlet on the west coast of Vancouver Island indicates a subduction earthquake and coseismic subsidence occurring in approximately that time frame (Enkin et al., 2013). This information is tantalizing for paleo-seismic researchers, who may be able to date earthquake events, and the converse case, that archaeologists may be able to date nearshore archaeological features, by comparing field observations to known paleo-seismic data (Enkin et al., 2013).

As mentioned in the results section, the clam gardens case study sites may be different ages due to the amount of exposure at different tide levels. An alternate theory is that the Russell Island clam garden was drowned during the inferred earthquake that
created the drowned forest at Island View beach about 2,000 YBP and had to be abandoned. The drowned forest on Island View Beach is potential evidence that a megathrust earthquake had impacts on sea level along south-eastern Vancouver Island and it is therefore likely that it had an impact in the region of the clam gardens on Saltspring and Russell Islands. Island View Beach is approximately 20 kilometres south of the aforementioned clam garden sites (Figure 3).
Figure 26. Drowned forest at Island View Beach on Eastern Vancouver Island. It was temporarily exposed after a spring wind storm in 2008. Note that this feature is not always exposed on the beach. During spring and summer 2015 for example, the feature could not be seen, presumably temporarily covered over again by the sands of the onshore sediment transport during a calm spring and summer season. White arrows indicate locations of drowned trees. Photos courtesy of Dr. A. Dallimore, Royal Roads University. Paleo-sea level researcher Dr. Tom James, of Natural Resources Canada, is pictured in the photo.¹

¹ Note: From Audrey Dallimore’s original photographs. Copyright 2008 by A. Dallimore. Reprinted with permission.
**Future Sea Levels**

Global predictions for sea level rise are quite variable and were not downscaled specifically to this region using general circulation models (GCM). This is due to the several different methodologies for doing the predictions as well as the general uncertainty in making any type of prediction. For example, Thomson et al. (2008) use tide gauge data for predictions. The IPCC (Church et al., 2013) uses a number of different GCM which are process-based models that take into account isostatic adjustment, thermal expansion of the ocean and melting in both Greenland and the Antarctic. While these models incorporate a lot of information, there is still a lot of variability within the predictions. Downscaling of GCM to local areas of B.C. has not yet occurred due to the large size of the typical IPCC model spatial grid of 100 to 200 kilometres, which is somewhat lower than the typical weather forecasting model, yet is still too large to incorporate all the geographic variability in a diverse landscape such as GINPR (Church et al., 2013). In addition, climate change overall is difficult to predict and local impacts can be theorized using scientific data but exact events are impossible to know. All of this points to the need for additional physical evidence, such as a core from an isolation basin to provide valuable local information on paleo-sea levels.

A significant point regarding rising sea levels is that the predicted sea level rise for the next few hundred years is similar to the rates that occurred during the last deglaciation. Humans are now a major forcing mechanism in the earth system, equal to times of profound natural change, such as glaciations, which built up over tens of thousands of years and not several centuries as the present time frame for changes due to global climate change are occurring.
Conclusion

The main conclusions of this thesis are: 1) modelling paleo and future sea levels is a valuable tool for communicating paleo-environmental, as well as future environmental information to non-specialists and particularly the public in GINPR, 2) sea level modelling is a valuable tool for GINPR as the clam garden management strategy is being created, 3) knowing where sea level has been gives clues where to look for archaeological and paleo geological features, and 4) knowing about regional paleo-sea levels and the present day exposure of the boulder walls can assist in estimation of relative ages of the features. Suggested future work to expand these ideas includes coring on Saltspring Island if an isolation basin can be found and the acquisition of more nearshore multibeam data to help focus on paleo shorelines and perhaps identify potential locations of archaeological rock walls.

Knowing where sea level may be in the future allows for coastal planning and mitigation measures. The comparison of the amount of past and future sea level rise in a case study area such as GINPR, can be important to impress on the public, planners and policy makers, the extent to which human activities are now considered a major forcing factor on the earth system, on the scale of global glaciations. The maps provide a compelling way to convey understandable information about future climate change coastal impacts. They can be easily accomplished with the ArcGIS methodology explained here, combined with a search through regional paleo-sea level literature, and the future sea level literature of recent IPCC report predictions. Most municipalities and National Parks, for example, would have the capacity to accomplish this analysis.
Outreach work done by Parks Canada and the Clam Garden Network is an important part of increasing public awareness of the clam gardens (Augustine et al., 2015). Exchanging information with First Nations in particular, may encourage further restoration and revitalization of clams gardens and other cultural traditions. In addition, outreach encourages discussion among scientists, First Nations and policy-makers regarding the environmental and cultural significance of these features. The Clam Garden Network website is an important scientific repository for the most recent and relevant information on clam garden research and First Nations knowledge sharing. The maps created during the course of this research also provide a valuable tool for community planners, policy makers and the public for the GINPR and south coastal Vancouver Island/Salish Sea area. Imparting scientific information, with eye catching visual displays, such as the maps displayed in this research as well posters, such as the Geoscape Series (Yorath et al., 2002), is an effective, great way to educate the public on both cultural and climatic history.
References


Barrie, J. V., & Conway, K. W. (2012). Palaeogeographic reconstruction of Hecate Strait British Columbia: changing sea levels and sedimentary processes reshape a glaciated...
Sea Level Change in the Gulf Islands National Park Reserve


Sea Level Change in the Gulf Islands National Park Reserve


Hetherington, R., Barrie, J. V., Reid, R. G., MacLeod, R., & Smith, D. J. (2004). Paleogeography, glacially induced crustal displacement, and Late Quaternary


Status of Research and Future Directions. In K. E. Graf, C. V. Ketron, & M. Waters (Eds.), *Paleoamerican Odyssey* (pp. 133 – 147). Texas A&M University Press.


Appendix A

In order to approximate what the sea level maps would look like with 100% data coverage, Adobe Fireworks was used to colour in some of the maps. Represented here are approximations for present day sea level, 55 metres below current sea level and 11.5 metres above sea level.

Figure A-1. Present day sea level. Full coverage approximation of Figure 10.
Figure A-2. Sea level at 55 metres below present day. Full coverage approximation of Figure 16.

Figure A-3. Sea level at 11.5 metres above present day. Full coverage approximation of Figure 25.