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<https://doi.org/10.15760/etd.1696>

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Relational Database Analysis of Dated Prehistoric Shorelines to Establish Sand
Partitioning in Late Holocene Barriers and Beach Plains of the Columbia River Littoral
Cell, Washington and Oregon, USA

by

Tamara Causer Linde

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geology

Thesis Committee:
Curt Peterson, Chair
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Portland State University
2014

ABSTRACT

Studies of episodic shoreline accretion of the Columbia River Littoral Cell (CRLC) have been ongoing since 1964. In this study, the sediment volumes in the late Holocene barriers and beach plains are compiled and formatted in GIS compatible databases for the four sub-cells of the CRLC.

Initial evaluation involved the creation of a geodatabase of 160 dated retreat scarp positions, that were identified on across-shore GPR and borehole profiles. Ten primary timelines were identified throughout the CRLC (0-4700 ybp) and those were used to develop polygon cells. Elevation, distance measurements, and position information were all linked to the polygon through a centroid location within the geodatabase.

Once the geodatabase was completed, data was imported into MSAccess™ to create a relational database that would allow for examination of the littoral cell in its entirety or of the individual sub-cells. Within the database, sediment volumes, ages, accretion rates, sediment thicknesses, and timeline relationships were calculated and recorded.

Using the database, the accretion history of the Columbia River Littoral Cell was evaluated and this examination illustrated the complexity of the system. Northern littoral transport was shown to be an important factor in the development of the littoral cell as a whole. Total sediment volume in the littoral cell was calculated to be $1.74 \times 10^9 \text{ m}^3$, with a mean accretion rate of $1.90 \times 10^4 \text{ m}^3/\text{yr}$, which is significantly less than some previous studies. This is due to a more detailed analysis of the beach and foredune facies

themselves. This is likely the result of the higher precision of beach and foredune surface information using LiDAR.

The database shows that the developmental history of the CRLC is dependent on temporal and spatial constraints that can be coupled with reverse modeling to predict shoreline erosion trends from impounded river sediments and potential global sea level rise. The North Beaches and Grayland Plains sub-cells have the greatest potential for future erosion; followed by the Clatsop Plains sub-cell.

DEDICATION

To my husband and daughter

Thank you for being the light on my darkest days.

Without your love, support, and patience this project would have never been
accomplished.

ACKNOWLEDGMENTS

I would like to thank my thesis advisor Curt Peterson for seeing potential in me and being there to provide guidance when I felt lost. I would also like to thank my thesis committee members Ken Cruikshank and Sandy Vanderburgh. Ken, thank you for teaching me the ins and outs of databases, without your patience and guidance I would have been very lost. Thank you Sandy for helping me to keep my writing focused. Thank you to David Percy for teaching me how to navigate my way through GIS and providing me with new ideas. Thank you to Scott Burns for being a mentor and helping me to grow as a scientist. I would also like to thank all of my friends for providing me with a sounding board and my family for keeping me grounded. Finally, I would like to express my deepest gratitude to Nancy Erikson for helping me to keep all of the paperwork in order, without you this would be a very difficult journey.

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1. INTRODUCTION

Analysis of the episodic shoreline accretion of the Columbia River Littoral Cell (CRLC) in Washington and Oregon (Figure 1) has been an ongoing process since Ballard's early work near the mouth of the Columbia River (Ballard, 1964; Phipps and Smith, 1978; Rankin, 1983). It was not until erosion of Peacock Spit (1977-1987) at the North Jetty (Phipps, 1990) that studies began with a focus on sand supply near the mouth of the Columbia River. As part of a multi-agency/institution study of the CRLC littoral system from 1996 to 2000 modern and prehistoric beach accretion rates were evaluated for the CRLC barriers and beach plains (Woxell, 1998; Peterson et al., 1999; Peterson et al., 2010a). These investigations were extended to include subsurface examinations of shoreface accretion (Herb, 2000; Peterson et al., 2010b; Vanderburgh et al., 2010). Other work including historic photo analysis and harbor-jetty system modeling (Martin, 2007) was focused on understanding erosional processes at bay mouth "hotspots" that had previously been stable or accreting after jetty construction in the early 1900's (Kaminsky et al., 2010; Ruggiero et al., 2010a).

Figure 1. The Columbia River Littoral Cell (CRLC) encompasses 165 km of shoreline along the coast of northwest Oregon and southwest Washington. The CRLC is divided into four sub-cells, Clatsop Plains, Longbeach, Grayland Plains, and North Beaches. Base map provided by ESRI (2013).

In this thesis a summary of the historic and prehistoric beach accretion rates are compiled and formatted in GIS compatible databases for the four sub-cells of the CRLC including: Longbeach, Clatsop Plains, Grayland Plains, and North Beaches. These accretion rates are useful for predicting which shoreline segments are most susceptible to future beach erosion either from declining sand supply and/or potential sea-level rise in the CRLC system (Gelfenbaum and Kaminsky, 2010).

The 165 km length of coastline from Point Grenville, Washington to Tillamook Head, Oregon has experienced net progradation during the late Holocene (5-0 ka) (Herb, 2000). While most of the historic shorelines in the CRLC prograded at rates exceeding several meters per year (Woxell, 1998), it is only during the last few decades that accretion trends have slowed and some local beach erosion has ensued (Gelfenbaum and Kaminsky, 2010). In this study, it is assumed that the progression of future shoreline erosion could be modeled in reverse order from the prehistoric trends of beach accretion. Subsequently, this study will provide a database of shoreline volume accretion throughout the four CRLC sub-cells during the late Holocene.

Net progradation of shorelines in the CRLC has occurred sequentially with increasing distance north of the Columbia River (Peterson et al., 2010b). The progradation of the beaches has been episodic as the barriers and the beach plains have cycled between periods of progradation and catastrophic retreat forced by tectonic strains events (Meyers et al., 1996). Widespread catastrophic retreat events within the CRLC resulted from prehistoric coseismic subsidence (Peterson et al., 2000) occurring in approximately 500 year intervals at the central Cascadia margin (Atwater et al., 2004).

Interseismic rebound of the coastline and replenishment of the near shore sand supply between subsidence events resulted in net beach accretion and allowed for the preservation of late Holocene records of the catastrophic retreat events (Peterson et al., 2010a).

Past studies of the CRLC (Woxell, 1998) showed that some of the catastrophic retreat features in the Longbeach Peninsula (Meyers et al., 1996) could be correlated throughout the four sub-cells. These correlations were tested by radiocarbon age, position relative to abandoned foredune ridges, and distinct sequences of large and small scarps identified in the GPR profiles. There are a maximum of 10 retreat scarps within the CRLC, seven of which are correlated between the four sub-cells (Peterson et al., 2010a). The seven regional retreat scarps are directly correlated to seven coseismic subsidence events along the Cascadia margin, which are reported to have occurred between 0.3 and ~3.2 ka (Atwater et al., 2004). The position of the dated retreat features are thought to represent the relative shoreline position within each sub-cell. Measurement of the changes in the prehistoric shoreline positions, between correlated subsidence events, in general reflects the littoral sand deposition within the four sub-cells (Peterson et al., 1999). Specifically, the measured net shoreline accretion between the dated shoreline positions represents sand volume added to the corresponding alongshore segments (Peterson et al., 2010a).

This study expands upon the analyses of episodic shoreline accretion in the CRLC (Woxell, 1998; Herb, 2000; Vanderburgh et al., 2010) by developing a relational database of published dune ridge trends (Rankin, 1983; Phipps et al., 2001; Reckendorf et al.,

2001), dated shoreline positions (Meyers et al., 1996; USGS and WDOE, 2002; Peterson et al., 2010b), and LiDAR topographic bounding surfaces (USGS, 2001) in the 165 km of coastline between northwest Oregon and southwest Washington. Query of the database records yields beach sand volume accumulation rates, at roughly 500 year time steps in polygon cells. The polygon cells are distributed across-shore and along-shore in each of the four sub-cells; North Beaches, Grayland Plains, Longbeach Peninsula, and Clatsop Plains. This information will aid in the predictive modeling of potential shoreline response to harbor sand management at the mouths of the Columbia River and Grays Harbor (USACE, 2012), potential decreased sediment supply from impounded Columbia River tributaries (Gelfenbaum and Kaminsky, 2010), apparent ongoing wave climate change (Ruggiero et al., 2010b), and future sea level rise predicted to occur from coseismic subsidence (Doyle, 1996; Peterson et al., 1999) and/or global warming (Aagaard and Sorensen, 2012).

Shoreline positions along the sand dominated shorelines of the CRLC vary over different temporal and spatial scales in response to changes in wave climate, sea level, sand supply, and artificial shoreline structures (Stive et al., 2002; Gelfenbaum and Kaminsky, 2010; Ruggiero et al., 2010a; Ruggiero et al., 2010b; Heathfield and Walker, 2011). Changing shoreline positions can influence residential developments, roadways, and other coastal infrastructure as well as wildlife habitat and beach recreational resources. Some of these impacts are already threatening coastal property, harbors, and roadways in the study area (Figure 2) (Kaminsky et al., 2010).

Figure 2. Location at the southern end of the Grayland Plains sub-cell that is currently undergoing coastal erosion.

The goals of this study are to expand upon the current understanding of sediment transport dynamics in the CRLC through calculations of episodic shoreline accretion rates, as established between dated shoreline retreat scarps or timelines, which are mapped throughout the CRLC beaches, barriers and beach plains. The spatial time-series records of beach accretion should be of use in calibrating shoreline accretion and erosion models in the CRLC, and as a general test of such models.

Specific objectives of this study include:

- Creation of a relational database using previously acquired ESRI-GIS mapped dune lines or shoreline orientations, and GPR across-shore profiles with associated dated retreat scarps or dated shoreline positions in the NAD83 horizontal datum.

- Establish computational methods for determining sand accretion surface areas in polygon cells, bounded between dated shoreline positions in across-shore GPR profiles.
- Use GPR established beach sand depths, and National Elevation Dataset (NED) coverage's in ESRI-GIS relative to NAVD88 elevation datum to calculate sand volumes and volume accretion rates in the polygon cells that are associated with shoreline timelines.
- Compare polygonal cell volume accretion rates in the CRLC sub-cells to local paleo-beach age, and distance from the Columbia River sand source.
- Examine partitioning of bedload sediment delivered from the Columbia River to barriers and beach plains of the CRLC during the late Holocene.
- Demonstrate the potential use of the reverse beach accretion history or back modeling to predict beach segments that are most sensitive to progressive beach erosion following either a decrease in Columbia River sediment supply and/or an increase in relative sea level.

2. BACKGROUND AND PREVIOUS WORK

The beaches of southwest Washington and northwest Oregon are identified as the subaerial component of the Columbia River Littoral Cell because their sediment originated from a common source, the Columbia River, and because they are bounded by Tillamook Head to the south and Point Grenville to the north, beyond which wide beaches do not occur (Figure 1) (Gelfenbaum and Kaminsky, 2010). The beaches of the 165 km littoral cell are separated by the Columbia River and two large estuaries to the north: Willapa Bay and Grays Harbor (Peterson et al., 2010b).

In the past century much of the shoreline of the CRLC prograded at rates of up to 3.0 meters per year which greatly exceeded prehistoric rates (Peterson et al., 1999). During this period of historic beach accretion, both common use and legal practices of shoreline development were followed in the CRLC study area. Over the last few decades, accretion has ceased throughout the littoral system and several erosional hot spots have developed adjacent to sub-cell boundaries at harbor mouths and jetties (Gelfenbaum et al., 1999). The decline in beach accretion is related to the progressive loss of flood tidal delta deposits (Phipps, 1990), exceptional El Niño conditions in 1993 and 1998 (Ruggiero et al., 2005), and possibly due to more intense storm wave action (Gelfenbaum and Kaminsky, 2010).

The coasts of Oregon and Washington are dominated by both active and inactive foredunes. The foredunes act as proxies for shore-parallel shoreline extensions between across-shore GPR profiles (Figure 3). The relationship between foredune development and coseismic uplift-subsidence cycles is beyond the scope of this study, however,

Meyers et al. (1996) mapped a coincidental 1:1 relationship between abandoned foredune ridges and prehistoric beach retreat scarps for the Longbeach Peninsula.

With the transition from an accreting coastline to an erosional coastline, the economic viability of many coastal communities will diminish (Sayce, 2000). The decrease in sediment supply to the CRLC impacts not only the beaches and foredunes, but also near-shore clam and shell fish industries that are already seeing a loss in production area (WDFW, 2012).

The CRLC provides an ideal environment to study the dynamics of coastal change in that it provides a system of prograded barriers, abundant sediment supply, high-wave energy, and large morphological changes resulting from active-margin dynamics, human alteration, and high sediment transport rates (Kaminsky et al., 2010)

Figure 3. Three distinct linear foredune ridges mapped in ArcGIS for the Longbeach sub-cell of the CRLC. Modified from Peterson et al. (2010a).

3. METHODS

In this study, dated retreat scarp positions located on across-shore GPR and borehole profiles identified by (Peterson et al., 2010a), were used to develop along-shore or paleo-shoreline timelines within each of the four CRLC sub-cells. The most landward extent of the retreat scarps were established by projecting the GPR retreat scarp reflections to the land surface. Errors and uncertainties in locating dated paleo-shoreline timelines are discussed in detail by Peterson et al. (2010a). Potential errors in age or position of the paleo-shoreline timelines are identified but not evaluated in this thesis and could be evaluated depending on future modeling requirements.

GPR traverses were not collected at the terminal ends of the bay spits or adjacent to the bay shorelines due to access limitations (Figure 1). To extend the paleo-shoreline timelines from the GPR traverses to the ends of the spits or to the shorelines, shore-parallel foredune ridges were used as proxies to extend the dated paleo-shorelines alongshore (Figure 4 and Figure 5). The foredune ridges are assumed to approximately represent paleo-shoreline positions shortly after the time of corresponding retreat events. Paleo-shoreline timelines are divided alongshore by the mapped GPR line traverses and bay shorelines, and special cases where timelines converge or older timelines are truncated by younger ones. The paleo-shoreline timelines and across-shore GPR traverses are also used to divide the enclosed areas into polygonal cells. This is defined later in this report (3.1 Polygonal Cell).

Figure 4. GPR identified scarp locations were used as to develop along-shore paleo-shoreline timelines. The foredune ridges were used as proxies for the dated paleo-shorelines. The foredune ridges are assumed to approximately represent paleo-shoreline trends following retreat events.

Figure 5. In image A, the LiDAR imagery allows for the visualization of the linear foredune ridges with plotted points indicating locations of retreat scarps. In image B, the foredune ridges and associated scarp positions are used to project the paleo-shoreline to the terminal end of the bay spit. These foredune ridges are assumed to approximate the paleo-shoreline trend at the time of each retreat event.

Foredune features are identified by high-resolution digital elevation models (DEM) produced from published LiDAR data sets. The bare ground LiDAR utilizes late return signals and other processing to subtract out vegetation and building elevations. To calculate sand volumes in the barrier and beach plains, the upper surface is evaluated for average elevation from published LiDAR DEMs (Gesch et al., 2009). Elevation raster files for the 1/9 arc second (3 m horizontal resolution) NED (Gesch et al., 2002; Gesch, 2007) were imported using NAD83 projection in ArcGIS. The NED data that were selected are the most current available, ranging from 2001-2005. A mosaic of the individual raster files (~32) was created to form a single base image for the 165 km study area. The raster mosaic was then processed using the 3D analyst toolbox to create a shaded relief map of the area.

3.1 Polygonal Cell

A database was created using Microsoft Access™ to tabulate the established paleo-shoreline locations on the GPR traverses (NAD83 UTM). A query table for the timeline positions on a GPR traverse was created for all four of the sub-cells. Each polygon is defined by the four line segments that connect the four intersections of the paleo-shoreline timelines and the GPR traverses (Figure 6).

Figure 6. Example of a polygon created using the intersection of GPR traverse lines and paleo-shoreline timelines.

Modern shoreline data for Oregon and Washington (0 m NAVD88) were added as line data in ArcGIS for use as termination points for both the along-shore timelines and the across-shore traverse lines (Washington State Department of Ecology, 1994; Oregon/Washington Bureau of Land Management, 2001). The addition of the modern shoreline data also allowed for the estimation of historic sand accretion since the last prehistoric retreat scarp (about 0.3 ka) (Peterson et al., 2010a) on the ocean side of the sub-cell spits. Each polygon cell is defined by line segments between the intersections of the paleo-shoreline timelines and the across-shore traverse or bay shorelines. In order to orient each polygon in space, the northeast, northwest, southwest, and southeast vertices for each polygon were identified and corresponding UTM positions were established.

3.1.1 Polygon Cell Centroids

The centroid of each polygon cell was created using the polygon to point operation in ArcGIS. The point was forced to be on the inside of the polygon for better visualization of the location (Figure 7). The horizontal coordinates of each centroid were determined using the add XY tool (coordinates in NAD83-UTM-Zone 10T).

Figure 7. Example of a polygon with centroid contained within the polygon. The centroid is the geometric center of the polygon.

The centroid serves as the point of reference for the polygonal cell. For example, the distance of the polygon cell from the modern shoreline is defined as the centroid position from the modern shoreline. Distances (north-south) are also calculated from the center of the modern Columbia River mouth to estimate the centroid distance to the primary littoral sand source, though the actual routes of littoral transport could be complex.

The mean, maximum, and minimum elevations for each of the polygons cells were calculated using the spatial statistics toolbox in ArcGIS. From the toolbox, the option of zonal statistics to table was chosen. The polygon cell layer was used to specify the zones and the unaltered DEM data were set as evaluation layer. The elevation values were returned in meters (NAVD88). The surface elevations of the polygon cells are the modern surfaces, based on the bare-earth LiDAR.

Distance between the polygon cell surface and an arbitrary basal elevation is used to obtain the average thickness of the beach sand facies, which includes both the prograded beach face deposits and the overlying dune ridge deposits (Figure 8). Basal elevation of the modern beach facies is taken to be 0 m NAVD88, as suggested by Peter Ruggiero (pers. comm. 2013, Ruggiero et al. (2013)). A paleo sea-level curve is used to project the basal elevations of the prehistoric beach deposits. The measured net long-term rate of sea level rise (1 m per 1000 yr) for the last several thousand years has been published for the study area (Peterson et al., 2010b). Cell age for each polygon is calculated as the median age between the bounding paleo-shoreline timelines and the polygon cell age is multiplied by the ratio of 1.0 m/ 1000 yr to yield the thickness of the polygon cell below the present day sea level. Total elevation difference between the modern surface and the basal elevation represents the combined thickness of the beach and dune deposits for each polygon cell.

Figure 8. Theoretical cross-section through the beach sand facies. Scarp locations were identified by GPR and projected to the surface as a point with UTM coordinates. The thickness of the polygon cell is estimated using the basal depth and average thickness of the median surface. Each polygon cell is bounded by the scarp points which were extended vertically downward from the median surface.

3.2 Database Development

The relational database developed for this study required identification of unique data, repeated data, and measured data. A requirement of the relational database is that information is not repeated. If information needed to be repeated, such as a vertex point shared in common between several polygons, a separate table of the unique values with a primary key was created. Using this process, several unique tables were created for this study. Each individual table has a primary key that is never repeated and it is only used once in that table. Relationships between the tables can then be made by using a foreign key that points to the primary key of another table.

For this analysis, 14 tables were created, each with a unique primary key (Figure 9). These tables were related using primarily 1 to 1 and 1 to many join types. Joins were

dependent upon relatable information between the tables. Constructed tables include: dune designation, feature type, scarp location, traverse profile, retreat scarp sequence, dune size, polygon identification, centroids, sub-cell, vertices, source location, direction from source, and timeline interval. For data associated with the polygonal cells, the centroid is used as the primary associative feature.

Scarp					
scarpID	transectID	featureID	sequenceID	utmID	Click to Add
1	MOCL1R1	SBRs	A	1	
2	COPR1R1	LBRS	A	2	
3	COPR1R1	FDDZ	C	3	
4	Joej1	SBRs	H	4	
5	227th	SBRs	C	5	
6	227th	LBRS	D	6	
7	RVDUNE	LBRS	A	7	
8	227th	SBRs	E	8	
9	RVDUNE	SBRs	C	9	
10	227th	LBRS	F	10	
11	CASI1R2	LBRS	A	11	
12	227th	BSDZ	G	12	
13	CASI1R2	SBRs	C	13	
14	227th	BSDZ	H	14	
15	CASI1R2	LBRS	D	15	

Figure 9. Example image of a table from the Access database. The tab label identifies the table name, and scarpID is the primary key for the table. The remaining columns (transectID, featureID, sequenceID, and utmID) are foreign keys relating to primary keys within other data tables, but are repeated within the Scarp Table or within the database.

3.3 Volume Calculations

Volume calculations were performed for each polygonal cell. This value for each polygon cell was determined by multiplying the GIS derived surface area of each polygon cell to the average thickness of the polygon cell. The thickness of the polygon cell was determined by calculating the difference between the average surface elevation and the projected basal elevation (Figure 10).

The polygon cell volumes are measured in cubic meters and these values can be converted to metric tons, if necessary, based on the published measures of sand bulk density.

To determine the approximate total volume of sand within each of the four CRLC sub-cells, all of the corresponding polygon cell volumes for each sub-cell were summed. The volume of sand accumulation between each retreat event or paleo-shoreline timeline was then totaled for each of the four CRLC sub-cells.

Figure 10. Illustration for the process of determining total beach and dune facies thickness. The mean elevation of the land surface (based on the polygon cell) is added to the basal elevation as based on the age of the polygon cell to calculate the total deposit thickness for each polygon cell. Note: This figure contains real data from the southern end of the Clatsop Plains sub-cell for use as a representative example.

4. RESULTS

4.1 Database

The study of the CRLC barriers and beach plain sand accretion rates required the development of two types of databases. The first database is an object-oriented relational database created in Access while the second is a geodatabase created in ArcGIS. The Access database contains location, measurement, and calculation data for the CRLC study area. The geodatabase contains spatial and imagery data used to develop the Access database.

There are 14 tables in the final Access database (Table 1). The individual tables are determined by unique characteristics pertaining to certain aspects of the database such as timelines, polygons, or centroids.

Table 1. List of Tables contained in the Access database.

Table Name	Description
Scarp*	Projected scarp surface positions based on GPR transects.
Transect*	Across-shore transects used to collect GPR profiles.
Sequence*	Sequence of correlated retreat features.
Size*	Vertical relief of foredune features.
Features*	Type of retreat feature.
Source	Description of primary sediment source for littoral cell.
Direction	Direction of sediment transport away from the sediment source.
Polygon	ArcGIS object identification and area measurements.
Centroid	Centroid for polygons. Used to anchor elevation data, distance to modern shoreline, and distance to sediment source for the polygon.
Interval	Timeline intervals with associated ages and depth below present sea level.
Sub-cell	Sub-cell names for larger littoral cell and data of accretion onset for the sub-cell.
Error	Table of potential data errors.
Vertices	Vertices positions for polygons and ArcGIS object identification.
UTM	Easting and Northing UTM coordinates based on NAD83-UTM-Zone 10T.
* Data reported in (Peterson et al., 2010a)	

The determination of which foreign keys to include in a given table is based on association of the data. For example, each polygon occupies a unique space and therefore has a primary key in the polygon table; however, the polygons were located on only one of four possible sub-cells (Figure 1). Since the determination of the sub-cell to which a polygon is associated will be repeated within the polygon table it is listed as a foreign key that then can be related to a table containing information unique to the sub-cells. This process enables the establishment of relationships between the various tables.

4.1.1 Database Tables

Within the database there are several pieces of data that are associated with UTM coordinates. The UTM Table contains all of the Easting and Northing coordinates within the database (Table 2). All of the coordinates are recorded using NAD83-UTM- Zone 10.

The coordinates within the UTM table are related to the table that they are associated with from Table 1.

Table 2. Subset of UTM coordinates with the Access database. Each coordinate is associated with the particular table that the datum correlates. Easting and Northing coordinates are based on NAD83 zone 10T.

utmID*	easting	northing	tableID [†]
763	407820	5233044	Vertices
1	407936	5232461	Scarp
408	408013	5231961	Centroid
762	408727	5228974	Vertices
758	410252	5218528	Vertices

*UTM primary key
[†]Foreign key that references the Table table

The sediment source for the CRLC is the Columbia River (Table 3). To understand sediment transport within the entire littoral cell the approximate center of the Columbia River mouth, at its confluence with the Pacific Ocean, was identified and recorded (Table 2). With this location identified, calculations regarding the distance of sediment travel throughout the littoral cell can be determined. In the CRLC, the examination of sediment transport is limited to north or the south of the Columbia River while secondary on-shore/off-shore transport cycles were not evaluated due to the complex nature of their association with sediment accretion to the beach plains of the CRLC.

Table 3. Table recording the position of the mouth for sediment source of the CRLC study area.

sourceID*	Source	utmID [†]
1	Columbia River Mouth	409

* Source primary key field
[†] Foreign key field referencing UTM table

The direction of sediment transport from the sediment source is defined in the direction table (Table 4). In the case of the CRLC sediment transport is either to the north or the south of the source. Since the sediment source in this research is limited to the

Columbia River it would not necessarily require a foreign key, however expansion of the data set to include other littoral cells would require this key distinction.

Table 4. Access database direction table which indicates the direction of sediment transport away from the sediment source for a given littoral cell or sub-cell.

directionID*	direction	source ID [†]
1	North	Columbia River Mouth
2	South	Columbia River Mouth
* Primary key field		
[†] Foreign key associated with sediment source		

In the sub-cell table, the data that are directly related to the four sub-cells of the CRLC are recorded. The table provides information on the name of each sub-cell and approximately how long ago seaward barrier accretion of the sub-cell began, based on back edge dates (Woxell, 1998). For each sub-cell the directions of the sub-cell from the Columbia River mouth sediment source are provided. This data is linked to a foreign key because the direction in this system can be either north or south (Table 5).

Table 5. Sub-cell table from the Access database that contains data regarding the approximate age of accretion onset for each sub-cell. A foreign key is assigned for the direction of each sub-cell from the sediment source.

subcellID*	nameSubcell	accretionOnset	directionID [†]
1	Clatsop	4000 ybp	South
2	Longbeach	4000 ybp	North
3	Grayland	2000 ybp	North
4	North Beaches	1500 ybp	North
* Primary key field			
[†] Foreign key field that relates to the Direction table			

In the transect table, data pertaining to the specific transects used in the collection of the GPR profiles are identified (Table 6). The foreign key associated with this table identifies the sub-cell that each transect is associated with. There are several transects within a sub-cell, however each transect can only exist on one sub-cell (Table 5). This distinction allows for ease of correlation with other data. The total number of transects

within each sub-cell differs due to variances in the length of the sub-cells and accessibility to certain areas due to development and property ownership.

Table 6. Example set of data from transect table in Access database. Transects run across-shore and are associated with one specific sub-cell. Within each sub-cell the number of transects that were performed varies by the length of the sub-cell and accessibility.

transectID*	transect	subcellID [†]
6	OHYU1R1	North Beaches
7	SRAIN1R1	North Beaches
8	LAMAR1R1	North Beaches
11	WEST1R2	Grayland
12	TWIN1R2	Grayland
13	MARD1R1	Grayland

* Transect table primary key field
[†] Foreign key field for association to Sub-cell table

There are four basic shoreline retreat feature types that can be found in the four sub-cells of the CRLC (Table 7). In this table, the short-hand terminology used to identify the four types of retreat features are defined in the feature Type column. There are no foreign keys associated with this table as these features do not relate to any other data tables.

Table 7. Feature table found in the Access database for the CRLC. The featureType column of the table shows the short-hand terminology used to identify the four types of retreat features found in the CRLC study area. Divisions based on Peterson et al. (2010a)

featureID*	feature	featureType
1	SBRS	small beach retreat scarp (3-5 m vertical relief)
2	LBRS	large beach retreat scarp (5-15 m vertical relief)
3	BSDZ	Backshore Disturbance Zone
4	FDDZ	Foredune Disturbance Zone

* Primary key field for Feature table

To define the primary types of foredune ridges in the study area a table of foredune height (size) was established. The width of the foredune ridges are not recorded due to variations that occur from the top of the dunes to the base that are non-uniform in nature. Each foredune ridge size is related to a range of reliefs from 1-15 m. The table

allows for the examination of the three size types: large, small, and very small (Table 8).

There is also a field designated as NA for instances where associated linear foredune ridges are not present, particularly in the case of expected retreat events. Foreign keys are not associated with this table as there are no linkages to other related data within this table.

Table 8. Foredune ridge size table from the Access database. The height (size) is based on the vertical relief of the linear foredune ridges. The NA case is for instances where a linear foredune ridge cannot be associated to a scarp position, particularly in the case of retreat events.

sizeID*	size	relief
1	Large	5-15 m
2	Small	3-5 m
3	Very-small	1-3 m
4	NA	0 m

* Size table primary key

The sequence table represents data associated with dated scarp timeline sequences. Unique data includes the sequence name and the age of the retreat event (Table 9). Retreat events are associated with linear foredune ridges which fall into one of three sizes of vertical relief requiring a foreign key to define the data (Table 8).

Table 9. Example of data contained in sequence table from Access database. Timelines can be associated with either shoreline retreat or subsidence following a seismic event. Retreat events are commonly associated with linear foredune ridges, these ridges tend to fall into three general size categories for the CRLC study area.

sequenceID	sequence	age	sizeID
3	C	1.3 ± 0.1 ka	Very-small
4	D	1.7 ± 0.1 ka	Large
5	E	2.5 ± 0.2 ka	Small
6	F	2.8 ± 0.2 ka	Large

* Primary key field for Sequence table

† Foreign key relating data from the Size table

§ Foreign key that references data from the designation ID

The scarp table contains data related to GPR identified scarps (Figure 8). The UTM east and north position for each scarp is identified as data in the table. Each scarp is

associated with a specific timeline sequence, transect, feature and sub-cell. Repeated data are connected to the scarp positions by the use of foreign keys such as transect associations (Table 10). Foreign keys associate to separate tables within the database where the parameter is more specifically defined.

Table 10. Example of information contained in scarp table of Access database. Each scarp location can have only one value from each associated foreign key table; however, the foreign key values can be repeated throughout the scarp location table.

scarpID*	transectID [†]	featureID [§]	sequenceID [#]	utmID**
1	MOCL1R1	SBRS	A	1
2	COPR1R1	LBRS	A	2
3	COPR1R1	FDDZ	C	3
4	Joej1	SBRS	H	4
5	227th	SBRS	C	5
6	227th	LBRS	D	6
7	RVDUNE	LBRS	A	7
8	227th	SBRS	E	8

* Scarp primary key identification
[†] Foreign key that references data from the Transect table
[§] Foreign key that references information found in the Feature table
[#] Foreign key that refers to the Sequence table
** Foreign key that refers to the UTM coordinate table

There are a total of 10 timelines identified for the CRLC including the modern shoreline, this represents a total of 11 unique timelines which run north-south. Within the CRLC study area, 14 unique timeline intervals were identified which represent the time between two adjacent timelines. Three of these intervals are due to instances where older timelines merge or are truncated by younger timelines. Between each timeline set, a period of accretion has taken place. To calculate the median age of the interval (centroid age), the age of the youngest timeline (minimum age) is subtracted from the age of the oldest timeline (maximum age) and divided by two, that result is then added to the younger timeline (minimum age). The median centroid age is used to calculate the paleo-

sea level curve for a given time interval (Table 11). The paleo-sea level curve determines the depth of the sediment within a polygon below the basal level of 0 m.

Table 11. Interval Table from Access database. The table provides information for the age of the youngest timeline in the interval (min age) and the oldest timeline (max age). The centroid age is the median age of the interval and is used to determine the sea level curve for each interval.

intervalID*	intervalName	minAge	maxAge	centroidAge
1	A/B	300	1100	700
2	B/C	1100	1300	1200
3	C/D	1300	1700	1500
4	D/E	1700	2500	2100
5	E/F	2500	2800	2650
6	F/G	2800	3200	3000
7	G/H	3200	4000	3600
8	H/I	4000	4700	4350
9	I/J	4700	5000	4850
10	B/D	1100	1700	1400
11	modern/A	0	300	150
12	F/I	2800	4700	3750
13	E/G	2500	3200	2850
14	A/C	300	1300	800
* Interval table primary key				

Polygons created in ArcGIS have several unique types of data. Each object within a shape file is given a primary key. In the geodatabase, the shape files are categorized by a sub-cell name leading some of the object identification keys to be repeated. For each polygon, the area is listed in both square kilometers and square meters for ease in calculation. The width of each polygon is based on the widest short axis length, while the length is based on the long axis. Several polygons exist within a single sub-cell allowing for a foreign key relationship with the sub-cell table. The primary vertex points for each polygon are listed for spatial association of the polygons to each other. This data was then recorded within the Access database (Table 12).

Table 12. Polygon table from Access database. Table contains primary data regarding the area of the polygon, as well as the length and width of the primary axes of the polygon. Linked data from other tables includes object identification key based off of ArcGIS polygons for each sub-cell, associated sub-cell, centroid identification, and the four vertices associated with the polygon.

polygonID*	polyArcID†	area_k m2	area_ m2	width_ m	length_ m	subcellID D§	centroidID D#	vertexID **
6	8	0.06	57,777	40	1669	Clatsop	6	11, 14, 15, 16
7	9	0.46	455,45 1	319	1674	Clatsop	7	15, 16, 17, 18
8	10	0.23	229,47 4	205	1685	Clatsop	8	17, 18, 19, 20
9	11	0.59	593,28 7	360	1846	Clatsop	9	19, 20, 21, 22

* Primary key field for Polygon table

† Foreign key relating to ArcGIS Polygon table. Relates to four different tables based on sub-cell.

§ Sub-cell foreign key

Foreign key linking the centroid to the polygon.

** Foreign key that relates to the primary vertices associated with each polygon

The individual polygons have four primary vertices that are located to the northeast, northwest, southeast, and southwest of each polygon. The vertices have unique positions in space; however, each vertex can be associated with up to four different polygons. The vertices assist in visualizing the polygon cell in a spatial context if access to ArcGIS is not available. The data table provides the UTM coordinates of each vertex, associated ArcGIS object identification number, and sub-cell location (Table 13).

Table 13. Vertices table containing positions for the four primary corners for each polygon cell.

vertexID*	vertArcID [†]	utmID [§]
79	1	111
143	1	72
144	2	552
145	3	70
146	7	554
80	8	488
147	8	68

* Primary key for polygon vertex locations

[†] Foreign key associated with ArcGIS vertex point data within each sub-cell

[§] Foreign key relating to the UTM coordinates for the vertex.

For each polygon there is a unique centroid with a distinct spatial location and this information is recorded in the centroid table. The centroid is also used as a means to tie other pertinent data to a polygon including mean, minimum and maximum elevation for the polygon. The centroid is also used as a base point for the approximate distance of the polygon to the modern shoreline and the mean distance from the Columbia River mouth. Foreign keys in the table include the sub-cell in which a centroid is located and the timeline intervals between which a polygon exists (Table 14).

Table 14. Centroid data table from Access database. Data on the mean elevation, minimum elevation, maximum elevation, and distance of the polygon centroid from the mouth of the Columbia River are provided. Associated sub-cell and timeline interval for the polygon are also recorded.

centroid ID*	meanElevati on m	minElevati on m	maxElevati on m	interval ID [†]	distShore km	distSource km	utmI D [§]
6	15.40	8.18104	21.65	A/B	0.25	26.23	166
7	13.80	7.32071	25.02	B/C	0.41	26.24	167
8	9.52	6.00122	13.84	C/D	0.61	26.32	168
9	6.92	1.91201	17.28	D/E	0.85	26.39	169

* Primary key for each centroid.

[†] Foreign key indicating the timeline interval for which the centroid is associated.

[§] Foreign key which relates to the UTM coordinates for each centroid location within the polygon.

The relationships between the different database tables are shown in Figure 11.

Relationships between the tables are based on shared information between and among the

tables. A good example of this is the sub-cell and its relationship to several other tables. There are only four sub-cells within the study area. Many of the tables present data that can be linked to specific sub-cells or to the study area as a whole, centroid distance from the modern shoreline or centroid distance from the Columbia River mouth. Without making the relationship between the data, data pertinent to a single sub-cell cannot be queried from the larger data set of the CRLC, while making each sub-cell a unique table to itself prevents examination of the CRLC as a whole. The relationships between the tables serve to make the data accessible for a variety of analyses.

To allow for future examination of the data contained within the database, a error table was created. This table includes information related to the estimated error for the measured data reported in the database (Table 15).

Table 15. Error table containing information pertaining to the errors associated with the measured data within the Access database.

errorID*	tableID [†]	accuracy	measurement
1	Scarp	10-50 m	projection UTM
2	Sequence	± 50-100 yr	age
3	Centroid	± 3 m	UTM
4	UTM	± 10 m	UTM
5	Polygon	± 1 m	elevation

*Primary key for error table
[†]Foreign key associated with table containing measured data.

Figure 11. Schematic diagram of the relationships between tables in the database. Image created by MS Access TM.

4.2 Littoral Sub-cells and Polygonal cells

The four littoral sub-cells in the CRLC (Figure 1) range from 21 km to 37 km in length and have an average width of 3 km. For these sub-cells, a total of 247 polygonal cells were created within the CRLC study area (Figure 1), based on dated paleo-shorelines and GPR traverses (Table 6 and Table 9). The number of polygon cells in each of the four littoral sub-cells area as follows: Clatsop Plains (53 polygon cells), Longbeach (97 polygon cells), Grayland Plains (43 polygon cells), and North Beaches (54 polygon cells) (Table 16). Each polygon cell is bounded by beach retreat scarps or paleo-shoreline timelines (A-J). In all four of the littoral sub-cells the youngest retreat timeline (A: 0.3 ka in age) is present. The oldest timeline (J: 5.0 ± 0.4 ka in age) is present in only two of the four littoral sub-cells (Table 16).

The most polygon cells are present in the Longbeach sub-cell, due to its greater age and longer length. The Grayland Plains sub-cell has the fewest number of polygon cells due to its young age, limited width, and position between Grays Harbor and Willapa Bay. Within the Clatsop Plains sub-cell, the age is similar to the Longbeach sub-cell, however the length of the sub-cell is more constrained due to prominent headlands at either end. For the North Beaches sub-cell, the age is similar to the Grayland Plains sub-cell and much of the northern end of the sub-cell is geologically much younger than any of the other sub-cells of the CRLC study area. However, the North Beaches sub-cell has a longer length in comparison to Grayland Plains, creating a need for more polygon cells.

Table 16. Summary table of parameters for the CRLC sub-cells.

Sub-cell Name	Timelines present	Direction from source	Number of polygon cells	Minimum surface elevation (m)	Maximum surface elevation* (m)
Clatsop Plains	A-J	South	53	0	34
Longbeach Peninsula	A-J	North	97	0	23
Grayland Plains	A-F	North	43	0	19
North Beaches	A-G	North	54	0	18

*Maximum surface elevation is based on maximum elevations found among all of the polygons within a given sub-cell

Polygon cell centroids are used to measure the polygon cell positions relative to the mouth of the Columbia River and the modern shoreline. The centroid located the furthest south is in the Clatsop Plains sub-cell, at a distance of 28.9 km from the Columbia River mouth. The centroid that is furthest north is in the North Beaches sub-cell, at a distance of 110.2 km from the Columbia River mouth. The distances from the centroid to the modern shoreline vary from 0.05 km to 4.01 km.

The polygon volume accretion data are outlined in the Results Section by distribution between the four littoral sub-cells (Figure 1). Polygon cell volumes are based on cell length, width, depth, and elevations. Minimum surface and depth elevations in all four littoral sub-cells are located at the modern beach face toe at 0 m NAVD88. Maximum dune ridge elevations within the entire CRLC range widely, from 3 m to 34 m NAVD88. Maximum surface elevations for each of the four littoral sub-cells are summarized as follows: Clatsop Plains (34 m), Longbeach (23 m), Grayland Plains (19 m), and North Beaches (18 m) (Table 16).

Polygon cell age, or the mid-point between bounding paleo-shoreline timelines was used as a basis for determining how deep to extend the basal beach facies elevation in each polygon cell. Basal elevation is estimated from the polygon cell age and the paleo sea-level curve of 1.0 m per 1000 years (see Methods; Figure 10). The youngest polygon cells, bounded by the shoreline timelines Modern/A have an age of 150 yr and a calculated basal elevation of -0.15 m NAVD88 (Table 17, Figure 10). The oldest polygon cells defined by bounding timelines I/J have an age of 4850 yr and a calculated basal beach facies elevation of -4.85 m NAVD88.

Table 17. List of timeline intervals found within the CRLC and associated centroid ages. Centroid ages were used to determine the depth to extend mean NAVD88 elevation data for each polygon cell.

Timeline interval	Polygon cell age (years)	Calculated depth below basal (meters below NAVD88)
Modern/A	150	-0.15
A/B	700	-0.70
A/C*	800	-0.80
B/C	1200	-1.20
B/D*	1400	-1.40
C/D	1500	-1.50
D/E	2100	-2.10
E/F	2650	-2.65
E/G*	2850	-2.85
F/G	3000	-3.00
G/H	3600	-3.60
F/I*	3750	-3.75
H/I	4350	-4.35
I/J	4850	-4.85

* One or more timeline intervals missing from the sequence.

A total beach and dune deposit thickness for each polygon cell was established by adding the mean surface elevation (+m NAVD88) calculated for each polygon cell and the corresponding basal beach facies elevation (-m NAVD88) converted to a positive

number (Figure 10). To determine the sediment volumes of the individual polygon cells, the mean sediment thickness was multiplied by the polygon surface area, as calculated by ArcGIS (see Methods; Figure 10). For the entire CRLC study area, the polygon cells range in volume from 60,739 m³ to 81,411,609 m³ (Appendix A).

4.2.1 Clatsop Plains

The Clatsop Plains sub-cell contains a total of 53 polygon cells. Data regarding the centroid positions, average elevations (m), average thicknesses (m), area (km²), computed volumes (km³), ages (min/max) and the centroid ages for each polygon cell are presented in Appendix A. Total sediment volume for the Clatsop Plains sub-cell from the modern shoreline to the oldest dated retreat scarp is ~0.614 km³. The largest volume accreted to Clatsop Plains (~0.119 km³) occurs within a paired timeline interval corresponding to the time interval E/F (Table 18). The timeline interval with the least volume accreted corresponds to the interval F/I, which was between 2.8 ka and 4.7 ka.

Table 18. Volume totals (km³) for each of the timeline intervals within the CRLC.

Timeline interval	Clatsop Plains	Longbeach	Grayland Plains	North Beaches	Total (km ³)
Modern/A	0.1095	0.1449	0.0777	0.1514	0.4835
A/B	0.0215	0.0221	0.0188	0.0094	0.0718
A/C	N.A.*	N.A.*	N.A.*	0.0065	0.0065
B/C	0.0311	0.0760	0.0256	0.0042	0.1369
B/D	0.0629	N.A.*	N.A.*	N.A.*	0.0629
C/D	0.0162	0.0674	0.0359	0.0124	0.1319
D/E	0.0874	0.0840	0.0285	0.0150	0.2148
E/F	0.1190	0.0520	0.0453	0.0082	0.2246
E/G	N.A.*	0.0002	N.A.*	N.A.*	0.0002
F/G	0.0548	0.0345	N.A.*	0.0031	0.0923
G/H	0.0506	0.0837	N.A.*	N.A.*	0.1343
F/I	0.0085	N.A.*	N.A.*	N.A.*	0.0085
H/I	0.0358	0.0368	N.A.*	N.A.*	0.0726
I/J	N.A.*	0.1018	N.A.*	N.A.*	0.1018
Total (km ³)	0.5973	0.7034	0.2317	0.2103	1.7428

*N.A. – not applicable, timeline interval does not exist within the sub-cell.

4.2.2 Longbeach

The Longbeach sub-cell contains a total of 97 polygon cells. The centroid positions, average elevations (m), average thicknesses (m), area (km²), computed volumes (km³), ages (min/max) and the centroid ages for each polygon cell are presented in Appendix B. Total sediment volume for the Longbeach sub-cell from the modern shoreline to the oldest dated retreat scarp is ~0.742 km³. On Longbeach Peninsula, the largest volume accreted (~0.145 km³) occurs within a paired timeline interval corresponding to the youngest interval Modern/A (Table 18). The timeline interval with the lowest accreted volume corresponds to the interval E/G, which was between 2.5 ka and 3.2 ka.

4.2.3 Grayland Plains

The Grayland Plains sub-cell contains a total of 43 polygon cells. Information on centroid positions, average elevations (m), average thicknesses (m), area (km²), computed volumes (km³), ages (min/max) and the centroid ages for each polygon cell are presented in Appendix C. Total sediment volume in Grayland Plains from the modern shoreline to the oldest dated retreat scarp is ~0.232 km³. For Grayland Plains, the largest volume accreted (~0.078 km³) occurs within a paired time-interval corresponding to the youngest interval Modern/A (Table 18). The timeline interval with the least volume accreted corresponds to the interval A/B, which was between 0.3 ka and 1.1 ka.

4.2.4 North Beaches

The North Beaches sub-cell contains a total of 54 polygon cells. Data for centroid positions, average elevations (m), average thicknesses (m), area (km²), computed volumes (km³), ages (min/max) and the centroid ages for each polygon cell are presented in Appendix B. Total sediment volume in North Beaches from the modern shoreline to the oldest dated retreat scarp is ~0.217 km³. In North Beaches, the largest volume accreted (~0.151 km³) occurs within a paired timeline interval corresponding to the youngest interval Modern/A (Table 18). The timeline interval with the least volume accreted corresponds to the interval F/G, which was between 2.8 ka and 3.2 ka.

4.2.5 Summary of Timeline Interval Beach Accretion

In this section, the total volumes for beach and dune sand accretion in the four littoral sub-cells are compiled for the entire CRLC. The greatest sediment volume (~0.477 km³) for the paired timeline interval corresponds to the youngest interval

Modern/A, whereas the least sediment volume (0.0002 km^3) for a paired time interval corresponds to the E/G interval which is only located on the Longbeach Peninsula (Table 18).

4.3 Across-shore Profiles

Within each of the sub-cells, across-shore profiles (methods; Figure 10) were taken for examination of the pattern of accretion within and between the sub-cells. Within the Clatsop Plains sub-cell, three along-shore profiles were created. In this area it is observed that the highest dunes move from the coastline at the southern end of the spit to the interior side of the bay mouth at the northern end of the spit (Figure 12). It is also observed that in the central and northern transects, the highest dunes are nearly twice as high as those observed in the southern transect.

For the Longbeach sub-cell, three along-shore profiles were taken at the northern, central, and southern regions of the developed spit (Figure 13). The linear ridge features are observed to be more uniform in height with very few of the foredunes exceeding 10 m in elevation. The highest foredune ridge is located near the shoreline in the northern profile with an elevation of nearly 20 m.

Two across-shore profiles for the Grayland Plains were taken near the north and south terminations of the existing spit (Figure 14). At the southern end of the spit there are three foredune ridges that dominate the profile with elevations between 9–15 m. Moving to the north, the foredune ridges present in the south all but disappear from the profile.

Two across-shore profiles were created for the North Beaches sub-cell (Figure 15) from both the southern terminal end and at the widest section of the spit that contained all of the representative timelines for the sub-cell. Examination of the profiles shows that the northern profile has three foredune ridges visible on the surface. These ridges are located bay side of the spit and are fairly close to each other. At the southern end there are no distinctive foredune ridges and the surface is relatively flat.

In comparing the sub-cell profiles, one noticeable variation between the profiles is the prominence of the foredune ridges. The only sub-cell to have distinctive foredune ridges in all three of the profiles is Clatsop Plains which is located to the south of the sediment source. Another observation is that the profiles taken in areas away from the terminal end that extends across a bay mouth has more distinctive foredunes. Potential relationships between beach plain, barrier accretion rates and corresponding foredune heights are explored in the Discussion Section of the thesis.

Figure 12. Across-shore profiles for Clatsop Plains sub-cell (10x vertical exaggeration). Each transect runs west to east, beginning at the modern shoreline and ending at the oldest intersecting timeline. Transect A is located near the northern end of the spit, transect B is located in the central portion of the spit, and transect C is located near the farthest extension of the along-shore timelines. Highest observed dune features migrate toward the coast as one looks from north to south.

Figure 13. Across- shore profiles for Longbeach sub-cell (10X vertical exaggeration) Each transect runs west to east beginning at the modern shoreline and terminating at the oldest intersecting timeline. The profiles are shown in order from the northern end (A) to the southern end of the spit. The largest dune in the Longbeach sub-cell is located at the northern end of the spit near the ocean shoreline.

Figure 14. Across-shore profiles for Grayland Plains sub-cell (10X vertical exaggeration). Transects are from the northern (A) and southern (B) ends of the spit. At the southern end it can be observed that there are three clearly defined foredune ridges, while at the northern end of the spit the ridges all but disappear.

Figure 15. Across-shore profiles for North Beaches sub-cell (10X vertical exaggeration). Transects are from the widest northern region (A) of the North Beaches developed spit and near the southern terminal end. In the profiles it can be observed that the highest foredune ridges are located at the northern end of the cell on the interior portion of the spit, while at the southern end the dunes are not a dominant feature on the landscape.

4.4 Error Analysis

A formal error analysis is beyond the scope of this thesis but such analysis could be included in future modeling efforts. In this regard several error estimates are provided for a hypothetical polygon cell, as defined in this thesis. Great earthquake retreat scarps are projected to the land surface along GPR traverses. The GPR traverses were geo-referenced by GPS (± 10 m error). As the polygon cells are several kilometers in length (along-shore) the length errors, based on traverse position error divided by total length, are on the order of 1.0% error. Greater length errors are likely to occur in polygon cells that border bay shorelines, as the transition from bay sediment to beach sediment is gradational. The length errors of these polygon cells could reach as much as 10% error if the bay-beach sediment interface position is uncertain to as much as 100 m. A more common problem arises with the polygon width estimates (across-shore). Extrapolation of the GPR retreat scarps to the land surface positions on the GPR traverse introduces potential position errors on the order of 10-50 meters (Peterson et al., 2010a). As most of the polygon cells are 368-564 m in width (Table 19), the potential errors of polygon widths, based on scarp-surface intersection errors and on GPS geo-referencing errors, are on the order of 10-20%. It is assumed that both the length and width estimate errors are random and will cancel to some degree with summing of multiple polygon cells for different beach accretion analyses.

Table 19. Summary of polygon widths for each of the CRLC sub-cells. The width of the polygon is based on the rectangular area around the polygon.

Sub-cell	Average (m)	Minimum (m)	Maximum (m)
Clatsop	550	29	5,465
Longbeach	382	40	2,583
Grayland	521	63	3,361
North Beaches	373	30	5,476

One systematic error that has been identified is the assumption that all polygon cells are bounded by vertical sides (Figure 8). Shoreface accretion surfaces are curvilinear (Cowell et al., 1995) but they are truncated in this study to simplify calculations of polygon cell volumes. As polygon shape errors are assumed to be symmetrical on the seaward and landward side of each polygon cell (trapezoid rectangle shape in cross-section) the estimated volume and associated accretion rates should not be significant, except perhaps, for the polygon cells in the most landward and seaward positions.

In terms of estimated accretion rates, the potential errors are associated with uncertainties of the earthquake age and subsequent shoreline erosion. Earthquake scarp age uncertainties are on the order of ± 50 -100 yr (AMS radiocarbon analytical error), so are reported to 0.1 ka (Peterson et al., 2010a). Assuming age uncertainties of ± 50 yr and polygon cells could have 10-20% errors in polygon cell ages (two-sided error). Because of shared age boundaries the summing of polygon cell accretion rates across several age intervals should drive down potential errors in estimated accretion rates due to potential uncertainty of polygon cell ages.

5. DISCUSSION

5.1 Database Analysis

With the use of both ArcGIS and the Access database, the resolution of the timeline analysis has been improved from previous studies. Early studies used three timelines determined from abandoned foredune ridges (Daniels, 2001), and in this study the number was increased to a total of 11 timelines. By increasing the timelines, the development history of the CRLC barriers and beach plains can be analyzed with increased accuracy and precision. This is the first study where accretion rates are tied to dated timelines. A database approach to the analysis of sediment volumes within the CRLC allowed for the examination of volumes within the four individual sub-cells, and as a combined unit. Previous examinations of the CRLC have estimated sediment accretion volumes based on linear surface thickness (Woxell, 1998) , or on the averaging of cross-sectional areas within each sub-cell (Herb, 2000; Peterson et al., 2010b). In this study, the sub-cells of the CRLC study area were broken into polygons to allow for higher spatial resolution along-shore and across-shore. This approach enables the variations in sediment accretion, both horizontally and vertically, to be taken into account when approximating sediment volumes.

5.2 Accretion Rates

Sediment accretion volumes for the four sub-cells of the CRLC were calculated for the polygonal cells (Table 20). Total sediment volume for the barrier and beach plains is calculated to be 1.74 km^3 , this is less than previous study estimates of $2.40 - 4.07 \text{ km}^3$ (Woxell, 1998; Gelfenbaum et al., 1999; Herb, 2000; Peterson et al., 2010b). Within the

CRLC study area, volumetric accretion rates vary and are affected by the distance from the Columbia River sediment source and amount of time for accretion to occur.

Volumetric accretion rates range from 152.8 m³/yr to 271,372.0 m³/yr across the entire CRLC study area with a mean of 18,985.3 m³/yr. The variations in the sediment accretion over time have been linked to several possible factors including the amount of sediment available to the littoral cell from the Columbia River, sediments available from the shelf, and the net littoral transport for a specific shoreline (Woxell, 1998; Herb, 2000; Peterson et al., 2010a).

Table 20. Sediment volume calculations for the beach plains and barriers and normalized sediment volumes for each of the sub-cells in the CRLC study area.

Sub-cell	Volume (m ³)	Normalize volume (m ³ /meter)*
Clatsop Plains	5.97 x 10 ⁸	153156
Longbeach Peninsula	7.03 x 10 ⁸	218333
Grayland Plains	2.32 x 10 ⁸	82589
North Beaches	2.10 x 10 ⁸	69185
Total	1.74 x 10 ⁹	523263
* Normalized units allow for the comparison of the sub-cells without taking length into account.		

5.2.1 Clatsop Plains

The Clatsop Plains sub-cell contains a total of 53 polygon cells. Data regarding the centroid positions, volumetric accretion rate (m³/yr), and time for accretion for each polygon cell are presented in Appendix F. In the Clatsop Plains sub-cell, the mean accretion rate from the modern shoreline to the oldest dated retreat scarp is 27,443 m³/yr (Table 21). The most rapid accretion rate for Clatsop Plains (224,478 m³/yr) occurred within the paired timeline interval corresponding to the time interval E/F. Interval A/B

had the slowest volumetric accretion ($482 \text{ m}^3/\text{yr}$), which was between 300 ka and 1100 ka.

Table 21. Summary of volumetric accretion rates for each sub-cell of the CRLC and for the entire littoral cell. Minimum and maximum volumetric accretion rates are based on the individual polygons within each sub-cell. The mean volumetric accretion rate is based on the entire sub-cell from the modern shoreline to the oldest dated retreat scarp.

Sub-cell	Minimum accretion (m^3/yr)	Maximum accretion (m^3/yr)	Mean accretion (m^3/yr)
Clatsop Plains	483	224478	27443
Longbeach Peninsula	253	158929	19798
Grayland Plains	274	62824	15937
North Beaches	153	271372	11651
Total*			18985
* Value based on Columbia River Littoral Cell as a whole.			

5.2.2 Longbeach

The Longbeach sub-cell contains a total of 97 polygon cells. Appendix F presents data regarding the centroid positions, accretion rate (m^3/yr), and time for accretion for each polygon cell. Within the Longbeach sub-cell the mean accretion rate from the modern shoreline to the oldest dated retreat scarp is $19,798 \text{ m}^3/\text{yr}$ (Table 21). The most rapid sediment accretion rate for the Longbeach sub-cell ($158,929 \text{ m}^3/\text{yr}$) occurred within the paired timeline interval corresponding to the time interval I/J. During the timeline interval A/B the slowest sediment accretion occurred ($253 \text{ m}^3/\text{yr}$), which was between 300 ka and 1100 ka.

5.2.3 Grayland Plains

There are a total of 43 polygon cells in the Grayland Plains sub-cell. Data regarding the centroid positions, accretion rate (m^3/yr), and time for accretion for each polygon cell are presented in Appendix F. For the Grayland Plains sub-cell the mean

accretion rate from the modern shoreline to the oldest dated retreat scarp is 15,937 m³/yr (Table 21). During the paired timeline interval modern/A the most rapid sediment accretion rate for Grayland Plains occurred (62,824 m³/yr). The timeline interval with the slowest sediment accretion corresponds to the interval A/B (274 m³/yr), which was between 300 ka and 1100 ka.

5.2.4 North Beaches

The North Beaches sub-cell contains a total of 54 polygon cells. Data regarding the centroid positions, accretion rate (m³/yr), and time for accretion for each polygon cell are presented in Appendix F. For the North Beaches sub-cell, the mean accretion rate from the modern shoreline to the oldest dated retreat scarp is 11,651 m³/yr (Table 21). The most rapid sediment accretion rate for North Beaches (271,372 m³/yr) occurred within the paired timeline interval corresponding to the time interval modern/A. The timeline interval with the slowest sediment accretion corresponds to the interval A/B (153 m³/yr), which was between 300 ka and 1100 ka.

5.3 Sub-cell Comparison

Using the database to examine individual sub-cells of the CRLC study area, it is observed that the slowest sediment accretion rate in all four occurred during the timeline interval A/B. The accretion rates during this time are lower by 2-3 orders of magnitude compared to all the other timeline intervals. There is slightly more variation between the sub-cells for which timeline has the greatest accretion rate with only a similarity between Grayland Plains and North Beaches. Reasons for these similarities and differences are

beyond the scope of this study, though an examination into this could provide insights into the system dynamics of the CRLC.

The database provides a unique tool for examination of possible trends or linkages for sediment accretion within the CRLC study area. Some of the possibilities include looking for trends in the polygon cell accretion rates and the distance the cell is from the mouth of the Columbia River, or examining if there is a difference between sediment accretion rates in the north versus that in the south (Figures 16 and 17).

There is not a visible trend in the sediment accretion rate and the distance of a centroid from the source (Figure 16). In the north there is also a lack of visible trend in the sediment accretion rate with distance from the Columbia River mouth (Figure 17).

Figure 16. Plot of the centroid distance south from the Columbia River mouth versus the shore normalized accretion rate of the centroid.

Figure 17. Plot of the centroid distance north from the Columbia River mouth versus the shore normalized accretion rate of the centroid.

A query of the Access database can also be used to examine sediment accretion rates for the different timeline intervals across the entire CRLC study area (Figure 18), or compare the sub-cells to each other (Figure 19). The accretion rate comparison of the 14 different timeline intervals shows that the most rapid mean accretion rate occurred during the I/J timeline interval (4.4 to 5.0 ka) while the slowest accretion rate occurred during the E/G timeline interval (2.5 to 3.2 ka). To get a picture of where the sand was accumulating during these two different intervals, the data can be examined by subdividing the data by sub-cell (Figure 19). This suggests that the most rapid and the slowest mean accretion rates occurred in the Longbeach sub-cell. Figure 19 allows for the comparison of the sub-cell within each timeline, which shows that there is variability in sediment accretion rate between the sub-cells.

Figure 18. Comparison of the mean shore normalized accretion rate for each timeline interval in the CRLC study area.

Figure 19. Comparison of the mean accretion rate in each of the timeline intervals for each sub-cell within the CRLC study area. Note: some timeline intervals are only present in a single sub-cell.

Using the geodatabase and the Access database in conjunction with each other, questions regarding certain spatial aspects of the CRLC can be examined. One such example would be to compare the sediment volumes at the terminal ends of a specific sub-cell (Table 22 and 23). Comparing the total sediment volume in Table 22 to the total sediment volume in Table 23, it is observed that there is more total sediment accumulated at the northern tip of the Grayland Plains sub-cell than at the southern tip. This is also apparent in the examination of the map as well as previous studies of the area. From this data it can also be observed in the two oldest time intervals (E/F and D/E), that the southern tip of the Grayland Plains had a higher sediment volume than the northern tip.

Table 22. ArcGIS identified polygon cells at the northern tip of the Grayland Plains sub-cell and sediment volumes for each polygon.

Sub-cell	Timeline Interval	Volume (m ³)	Normalized volume (m ³ /m)
Grayland	Modern/A	1.88 x 10 ⁷	4956
Grayland	A/B	4.04 x 10 ⁶	2006
Grayland	B/C	4.79 x 10 ⁶	2467
Grayland	C/D	3.96 x 10 ⁶	2025
Grayland	D/E	7.29 x 10 ⁵	455
Grayland	E/F	9.77 x 10 ⁵	678
Total		3.33 x 10 ⁷	12587

Table 23. ArcGIS identified polygon cells at the southern tip of the Grayland Plains sub-cell and sediment volumes for each polygon.

Sub-cell	Arc Object ID	Volume (m ³)	Normalized volume (m ³ /m)
Grayland	Modern/A	3.02 x 10 ⁶	2408
Grayland	A/B	1.26 x 10 ⁶	1060
Grayland	B/C	2.61 x 10 ⁶	1456
Grayland	C/D	5.50 x 10 ⁶	2448
Grayland	D/E	3.76 x 10 ⁶	1897
Grayland	E/F	3.34 x 10 ⁶	1663
Total		1.95 x 10 ⁷	10932

5.4 Developmental Progression

The developmental progression of the CRLC study area can be examined by looking at the sediment accretion in the sub-cell over time. Using the information from Figure 20 and Table 24 a development history of the CRLC study area can be created working from the oldest timeline to the youngest. Following the first seismic retreat event identified in the CRLC, the Longbeach sub-cell was the first to experience accretion with an average rate of 23.52 m³/year. After the 4.7 ka event, the Clatsop Plains sub-cell began to experience recovery accretion and the accretion rate for Longbeach slowed. A retreat event for the Grayland Plains sub-cell did not occur until the 3.2 ka event. The accretion rate for Grayland Plains was the slowest of all the sub-cells following most of the retreat events. The first seismic retreat in the North Beaches sub-cell occurred in 2.8 ka, which is a strong indicator that of the four sub-cells it was the last to form. Interestingly, the mean accretion rate of North Beaches is commonly higher than Grayland Plains though it is farther north, though reasons for this are not readily apparent.

Figure 20. Total sediment accretion volumes through time for each of the sub-cells in the CRLC.

Table 24. Mean accretion rates (m^3/year) for each timeline interval broken down by individual sub-cells of the CRLC study area, from oldest interval to youngest.

Interval	Clatsop	Longbeach	Grayland	North Beaches
I/J		23.52		
H/I	2.60	2.21		
G/H	2.87	3.34		
F/G	4.96	2.87	0.90	
E/F	15.05	5.93	1.65	7.45
D/E	5.15	3.12	1.96	1.84
C/D	4.14	4.70	2.53	4.80
B/C	19.53	12.16	3.13	6.17
A/B	0.89	0.80	0.56	1.12
Modern/A	12.49	12.45	10.68	12.38

To estimate the erosion potential of the CRLC, backward modeling can be performed (Figure 21). Generally, the last area to accrete is the first to erode. If this

assumption is used then the northern most end of North Beaches will be the first to begin to erode. Mean accretion rates in the Grayland Plains sub-cell indicate that erosional processes will have a strong influence there, due to lower accretion rates relative to the other three sub-cells.

Figure 21. Estimated sediment erosion through reverse modeling. North Beaches and Grayland Plains would be first impacted by sediment erosion due to later development and less accretion through time.

5.5 Future Applications

The database developed in this study has revealed that there are still several questions that remain unanswered regarding the CRLC. An examination of the forcing processes occurring within the CRLC could be examined as part of a future modeling effort. Possible reasons for the variations in accretion rates could be associated with available accommodation space within each of the sub-cells. As the foreshore area fills

with sediment, accommodation space is lost and sediment must be transported further along-shore. In the case of a seismic event, some areas may gain or lose accommodation space creating changes in sediment transport patterns.

Sediment transport patterns could play a strong role in the movement of sediment along the shore particularly in the CRLC due to a unique variation in littoral transport direction between winter and summer (Figure 22). The dominant littoral transport within the CRLC is to the north; however, seasonal variations in littoral transport may be influencing the interaction of accretion and shelf development. Examination of the transport of sediment within the CRLC is currently lacking information regarding the interaction of the shelf deposits with the beach plains. With this study and previous studies, sediment volumes in both the beach plains and on the shelf have been determined; an extension of these studies would be to apply modeling to examine the interactions between the two sediment areas to evaluate the sediment transport dynamics of the system as a whole.

Figure 22. Depiction of sediment transport due to littoral drift during the winter season in the CRLC. Waves in the winter tend to have high energy and move predominantly to the northeast inducing a strong northern longshore transport. In the summer the waves are predominantly to the southeast and have lower energy causing a slight southern longshore transport.

Examination of the effects of shoreline orientation on sediment transport could also yield interesting insight into the developmental history of the CRLC. The unique curvature of the CRLC has the potential to influence the movement of sediment within the littoral cell and the sub-cells. Modeling of this may help in the understanding of why some dune ridges are more prominent than others and why there is high sediment accretion in some locations and not in others.

Examination of these different forcing effects within the CRLC through modeling could allow for the adjustment of current management practices along the coastline. This becomes increasingly important as development along the coastline increases and the natural system dynamics are altered.

6. CONCLUSIONS

There are sufficient constraints on the barriers and beach plains to develop a relational database for use in the calculation of volume and accretion rates within the four sub-cells of the CRLC system.

By using the Access database complex questions can be asked about sediment volumes, distances of polygon centroids to the modern shore or Columbia River mouth, polygon elevations, sub-cells. The results of these questions can provide new insight into the movement and distribution of sediment within the CRLC, as well as predicting susceptibility to future beach erosion.

The total volume of sediment deposited during the late Holocene (5-4 ka) within each of the four sub-cells are as follows:

- Longbeach Peninsula: $7.03 \times 10^8 \text{ m}^3$ since $5.0 \pm 0.4 \text{ ka}$
- Clatsop Plains: $5.97 \times 10^8 \text{ m}^3$ since $4.7 \pm 0.2 \text{ ka}$
- Grayland Plains: $2.32 \times 10^8 \text{ m}^3$ since $2.8 \pm 0.2 \text{ ka}$
- North Beaches: $2.10 \times 10^8 \text{ m}^3$ since $3.2 \pm 0.2 \text{ ka}$.

The mean accretion rates for each of the four sub-cells provide information of the variability of sediment deposition through time. Based on this data there is not a general trend in the depositional history and using the timelines as a function of deposition history is the most practical approach. There is variability in the accretion rates between each retreat event, the influences of this are of interest, though they fall outside of the focus of this study.

Table 25. Accretion rates for each of the nine timeline intervals in the CRLC. Based on shoreline normalized values.

Timeline interval	accretion rates (m ³ /m/yr)
I/J	23.52
H/I	2.39
G/H	3.16
F/G	2.90
E/F	7.30
D/E	2.30
C/D	4.18
B/C	9.09
A/B	0.82

Specifically, this study addresses the partitioning of bedload sediment delivered from the Columbia River to the barriers and beach plains of the CRLC during the late Holocene. With future evaluation of the data and modeling, some of the questions that were brought forward with regard to the CRLC may be addressed. There is also the potential to use this database as a model for future database creation. An important outcome of this study is that it has demonstrated the succession of accretion from the addition of Columbia River sediments, and, when the process is examined in reverse, it could potentially predict the erosion of sediments with decrease sediment supply (last deposited, first eroded).

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Appendix A Clatsop Plains

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Ave Thickness (m)	Volume (m ³)
429624	5095105	3.88	2800	4700	3750	1,115,357	7.6	8512429
429489	5097304	6.72	2800	3200	3000	270,106	9.7	2624804
429665	5097482	5.05	3200	4000	3600	309,228	8.7	2675459
429793	5097307	5.30	4000	4700	4350	130,159	9.6	1255932
428249	5097565	11.47	0	300	150	376,957	11.6	4381524
428380	5097526	15.40	300	1100	700	57,778	16.1	930504
428534	5097558	13.80	1100	1300	1200	455,452	15.0	6832371
428740	5097545	9.52	1300	1700	1500	229,475	11.0	2527856
428980	5097553	6.92	1700	2500	2100	593,288	9.0	5349391
429278	5097514	6.17	2500	2800	2650	458,958	8.8	4047037
428372	5099084	11.65	300	1100	700	35,866	12.3	442859
428229	5099165	11.95	0	300	150	375,836	12.1	4546372
428515	5099137	16.57	1100	1300	1200	382,912	17.8	6805195
428701	5099122	11.31	1300	1700	1500	164,843	12.8	2112369
428927	5099192	7.53	1700	2500	2100	538,398	9.6	5186756
429252	5099082	8.90	2500	2800	2650	465,272	11.6	5375770
429447	5099289	7.25	2800	3200	3000	265,328	10.3	2720114
429686	5099150	6.72	3200	4000	3600	533,112	10.3	5499428
429892	5099391	6.93	4000	4700	4350	112,909	11.3	1274029
427869	5102930	11.68	0	300	150	1,848,939	11.8	21879978
427912	5104559	10.72	300	1100	700	343,690	11.4	3926385
428430	5100885	16.72	1100	1300	1200	974,082	17.9	17456913
428112	5104742	13.66	1300	1700	1500	616,697	15.2	9350230
429209	5102333	8.55	2800	3200	3000	1,278,348	11.5	14759776
428608	5102665	10.13	1700	2500	2100	2,240,247	12.2	27402920
428798	5103988	14.19	2500	2800	2650	1,390,241	16.8	23409287
429312	5103450	9.32	3200	4000	3600	1,318,250	12.9	17031627
429500	5103151	7.52	4000	4700	4350	621,292	11.9	7376275
427949	5105969	14.56	1300	1700	1500	136,808	16.1	2197313
427100	5107067	9.84	0	300	150	1,552,277	10.0	15507468
427339	5107161	13.79	300	1100	700	140,657	14.5	2037868
427489	5107388	16.87	1100	1700	1400	1,098,360	18.3	20071972
427900	5107265	12.13	1700	2500	2100	1,048,109	14.2	14909776
428234	5107156	14.81	2500	2800	2650	867,163	17.5	15142929
428471	5107024	8.44	2800	3200	3000	336,632	11.4	3852312
428731	5106190	9.58	3200	4000	3600	242,837	13.2	3200791
428419	5108039	9.25	4000	4700	4350	695,924	13.6	9463189

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Ave Thickness (m)	Volume (m ³)
427439	5109061	12.63	1700	2500	2100	256,624	14.7	3781016
427020	5109042	18.96	1100	1700	1400	273,364	20.4	5566448
426513	5109057	10.12	0	300	150	375,120	10.3	3853574
426786	5109083	9.92	300	1100	700	36,357	10.6	386281
427788	5109096	14.43	2500	2800	2650	217,190	17.1	3708890
427971	5109133	8.52	2800	3200	3000	55,092	11.5	634416
428065	5109170	7.44	3200	4000	3600	89,930	11.0	992604
428207	5109133	11.84	4000	4700	4350	120,231	16.2	1946833
428239	5113819	5.55	4000	4700	4350	1,466,664	9.9	14521043
428395	5114636	5.57	3200	4000	3600	2,313,905	9.2	21215759
428220	5115393	3.91	2800	3200	3000	4,366,029	6.9	30188646
425929	5115885	8.01	2500	2800	2650	6,319,360	10.7	67343335
426200	5112911	7.90	1700	2500	2100	3,079,345	10.0	30788955
426499	5110972	12.99	1100	1700	1400	2,590,566	14.4	37267362
424921	5115165	8.81	300	1100	700	1,447,435	9.5	13768942
423907	5116499	5.49	0	300	150	10,505,946	5.6	59304069

Appendix B Longbeach Peninsula

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Average Thickness (m)	Volume (m ³)
418649	5131069	6	1300	1700	1500	16201	7	114590
418585	5130970	7	1100	1300	1200	48045	8	372908
418528	5130994	7	300	1100	700	27179	7	202764
418158	5131021	6	0	300	150	391631	6	2369659
419347	5130961	5	4000	4700	4350	310029	10	2992339
419047	5131078	5	3200	4000	3600	345331	9	2984289
418733	5131021	6	1700	2500	2100	109030	8	853678
418858	5131225	6	2500	3200	2850	25214	9	226530
419813	5133034	5	4000	4700	4350	667901	10	6523598
420266	5132403	4	4700	5000	4850	5118550	9	47678627
419546	5132592	5	3200	4000	3600	960824	9	8235405
419386	5132827	5	2800	3200	3000	481970	8	4009781
419445	5133878	5	2500	2800	2650	540480	8	4252634
419177	5133650	6	1700	2500	2100	1094711	8	8323573
418954	5133130	6	1300	1700	1500	149449	7	1114972
418895	5133782	6	1100	1300	1200	900483	7	6583812
418714	5133350	7	300	1100	700	220019	8	1780363
418363	5133342	6	0	300	150	2676738	6	17310975
420648	5136414	4	4700	5000	4850	1456892	9	13575655
420281	5136540	7	4000	4700	4350	124524	11	1351850
420110	5136368	5	3200	4000	3600	517600	9	4429203
419975	5136579	5	2800	3200	3000	145907	8	1184260
419821	5136457	6	2500	2800	2650	434804	9	3815184
419541	5136414	5	1700	2500	2100	718663	7	5088823
419363	5136680	6	1300	1700	1500	126413	7	930643
418896	5136472	8	300	1100	700	80099	9	704784
419115	5136486	6	1100	1300	1200	823537	7	6035495
418566	5136453	7	0	300	150	1277575	7	8833151
419492	5138019	5	1300	1700	1500	121799	7	842495
419216	5137996	6	1100	1300	1200	430688	7	3152206
418984	5138004	7	300	1100	700	40557	8	306071
418674	5138001	7	0	300	150	585506	7	4147142
419686	5137981	5	1700	2500	2100	280850	7	2032257
420813	5138019	5	4700	5000	4850	758230	10	7217226
420431	5138049	6	4000	4700	4350	100120	11	1085897
420287	5138029	6	3200	4000	3600	216164	9	2043361

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Average Thickness (m)	Volume (m ³)
420138	5138025	5	2800	3200	3000	116534	8	948131
419958	5138043	6	2500	2800	2650	285790	9	2479082
421068	5140914	5	4700	5000	4850	3250844	10	33319911
420659	5140814	7	4000	4700	4350	415790	12	4823927
420478	5141110	6	3200	4000	3600	1388154	10	13936090
420266	5140886	6	2800	3200	3000	469185	9	4278033
420091	5140716	6	2500	2800	2650	1086910	9	9718052
419822	5141113	6	1700	2500	2100	1591308	8	12357525
419525	5141164	7	1300	1700	1500	1178388	8	9614560
419268	5140610	6	1100	1300	1200	1286085	8	9833795
419089	5141295	7	300	1100	700	523789	8	4191780
418772	5140810	7	0	300	150	2470519	7	18131337
420851	5145039	7	4000	4700	4350	415171	11	4673389
420595	5144690	7	3200	4000	3600	1147367	10	11657927
420375	5144766	7	2800	3200	3000	246152	10	2421223
420262	5144659	7	2500	2800	2650	434475	10	4221069
419974	5144880	6	1700	2500	2100	1440342	8	11725966
419557	5144955	6	1300	1700	1500	1169044	8	9298903
419091	5144747	8	300	1100	700	251758	9	2185397
419249	5144880	8	1100	1300	1200	731565	9	6544096
418857	5144889	7	0	300	150	1195497	8	8995240
420813	5147922	5	4000	4700	4350	1557157	10	15335914
420480	5149208	6	3200	4000	3600	1814549	10	17588261
420254	5149070	9	2800	3200	3000	507277	12	5850965
420046	5150395	8	2500	2800	2650	620928	10	6372194
419891	5148793	7	1700	2500	2100	2151299	9	19063222
419457	5148869	7	1300	1700	1500	2160475	9	18544052
419208	5148313	9	1100	1300	1200	549626	10	5427245
419062	5150356	7	300	1100	700	379453	8	3042993
418888	5148843	7	0	300	150	1703103	7	12737627
419013	5152046	6	300	1100	700	136775	7	936502
419301	5153811	8	1100	1300	1200	1571097	9	14504888
418868	5153702	7	0	300	150	1406133	7	9615686
419666	5153739	6	1300	1700	1500	1289499	8	10229186
419676	5152153	7	1700	2500	2100	720590	9	6477477
420129	5153489	7	2500	2800	2650	1347691	9	12473486
420352	5153779	7	2800	3200	3000	333120	10	3253583
420580	5153262	6	3200	4000	3600	1915031	10	18229714

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Average Thickness (m)	Volume (m ³)
418892	5156253	6	0	300	150	792429	7	5249501
419189	5156202	13	300	1100	700	73338	14	990196
419434	5156189	7	1100	1300	1200	646601	8	5137102
420870	5156285	3	3200	4000	3600	280892	7	1981353
420693	5156357	5	2800	3200	3000	209681	8	1664983
420509	5156223	7	2500	2800	2650	285345	10	2813834
419886	5156233	6	1300	1700	1500	653842	7	4775940
420261	5156333	6	1700	2500	2100	407611	8	3300997
421248	5157503	3	3200	4000	3600	392663	7	2564456
419219	5158386	12	300	1100	700	281370	12	3508742
419440	5158461	7	1100	1300	1200	1045652	8	8663527
419852	5158457	5	1300	1700	1500	1360914	7	9017470
420315	5158532	5	1700	2500	2100	1325589	7	9756255
418818	5158438	6	0	300	150	2057421	6	13215968
420678	5158657	5	2500	2800	2650	691655	7	5064774
421096	5158519	4	2800	3200	3000	1644013	7	10691197
421125	5159969	4	2800	3200	3000	23142	7	172156
420926	5160077	4	2500	2800	2650	121246	7	825075
420476	5160475	4	1700	2500	2100	795259	6	5031296
420007	5160583	4	1300	1700	1500	499495	6	2952026
419737	5161130	6	1100	1300	1200	1301805	7	9698879
419512	5161657	9	300	1100	700	428305	10	4237390
418755	5163514	5	0	300	150	9162952	5	44320190

Appendix C Grayland Plains

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Average Thickness (m)	Volume (m ³)
417826	5176367	5	1100	1300	1200	434591	6	2605705
416725	5177130	4	0	300	150	677028	4	3022086
417866	5177033	5	1300	1700	1500	884687	6	5503401
418404	5176922	4	1700	2500	2100	591070	6	3760127
418724	5176983	5	2500	2800	2650	420502	8	3340503
418405	5178883	6	2500	2800	2650	1031032	8	8547754
418034	5178786	5	1700	2500	2100	812702	7	5478270
417608	5178703	5	1300	1700	1500	1303488	6	8269156
417301	5178564	7	1100	1300	1200	292813	8	2263441
417200	5178200	7	300	1100	700	213504	8	1675035
416677	5178795	6	0	300	150	2465174	6	14656446
417991	5181385	6	2500	2800	2650	1283418	9	11061907
417648	5181340	5	1700	2500	2100	659056	8	4949932
416566	5181376	6	0	300	150	2127900	6	13279842
417364	5181375	5	1300	1700	1500	894640	7	5873534
416839	5182546	8	300	1100	700	251124	9	2271915
417105	5181530	5	1100	1300	1200	468444	7	3058717
416520	5184544	6	300	1100	700	449731	7	3237940
416709	5184333	5	1100	1300	1200	521318	6	3274675
416223	5184403	6	0	300	150	1635506	6	10029019
416889	5184399	5	1300	1700	1500	709923	6	4537138
417077	5184371	5	1700	2500	2100	466430	7	3340804
417283	5184711	6	2500	2800	2650	1370316	8	11202456
416660	5187532	6	2500	2800	2650	906206	8	7631224
416158	5187972	5	1300	1700	1500	569767	7	3962000
416243	5188454	5	1700	2500	2100	808389	7	6011155
415807	5188131	8	300	1100	700	530475	8	4365534
415901	5188424	6	1100	1300	1200	688495	7	4878893
415590	5187978	6	0	300	150	1511649	6	9687145
415326	5191308	6	1100	1300	1200	630530	8	4766697
415152	5191369	9	300	1100	700	207127	9	1913281
414828	5191395	6	0	300	150	1353637	6	8157937
416025	5190703	10	2500	2800	2650	200802	13	2515679
415542	5191483	5	1300	1700	1500	580261	7	3806775
415787	5191281	6	1700	2500	2100	547492	8	4197179
415958	5193256	5	2500	2800	2650	135664	7	977137
415875	5193266	4	1700	2500	2100	121602	6	729285

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Average Thickness (m)	Volume (m ³)
416657	5193802	2	1100	1300	1200	17132	4	61612
415633	5193380	4	1300	1700	1500	759309	5	3957532
416768	5193936	2	300	1100	700	80647	3	218963
415301	5193412	5	1100	1300	1200	720288	7	4729044
415827	5194368	4	300	1100	700	818940	5	3821182
414832	5194420	4	0	300	150	4058772	5	18847192
417220	5176851	5	300	1100	700	229785	5	1262702

Appendix D North Beaches

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Average Thickness (m)	Volume (m ³)
412077	5201359	5	0	300	150	17022209	5	81411609
412701	5202602	7	300	1100	700	256044	7	1855163
412432	5204738	5	1100	1300	1200	173633	6	1059065
412831	5203512	4	1300	1700	1500	1624020	5	8904179
413221	5202728	5	1700	2500	2100	840047	7	5883882
413197	5203905	5	2500	2800	2650	856869	8	6666640
413135	5204910	4	2800	3200	3000	65689	7	485272
411531	5206127	5	0	300	150	1284283	6	7158375
412198	5206183	7	300	1100	700	58129	8	454820
412291	5206184	6	1100	1300	1200	128687	8	972037
412480	5206143	5	1300	1700	1500	241689	6	1549532
412698	5206152	5	1700	2500	2100	196920	8	1490655
412815	5206191	6	2500	2800	2650	53615	8	437379
412865	5206172	5	2800	3200	3000	38520	8	315364
412707	5206908	5	2800	3200	3000	15814	8	126231
412656	5206928	5	2500	2800	2650	28290	8	224179
412550	5206931	5	1700	2500	2100	79135	7	576172
412383	5206930	5	1300	1700	1500	95850	7	626958
412227	5206932	7	1100	1300	1200	71199	8	561300
411500	5206920	6	0	300	150	671403	6	3947113
412127	5206944	8	300	1100	700	37000	8	307378
412591	5207409	5	2800	3200	3000	18625	8	140912
412555	5207396	5	2500	2800	2650	22512	8	170862
412442	5207464	5	1700	2500	2100	77017	8	581521
412324	5207419	5	1300	1700	1500	53036	7	362364
412144	5207466	6	300	1100	700	18439	7	122202
412214	5207464	6	1100	1300	1200	55581	7	401598
411510	5207486	6	0	300	150	674280	6	4079521
412579	5208994	3	2800	3200	3000	51962	6	333841
412444	5207962	4	2500	2800	2650	51020	7	331890
412281	5208649	6	1700	2500	2100	454669	8	3571283
412106	5208619	7	1300	1700	1500	89548	8	727205
411988	5209100	7	1100	1300	1200	79784	9	687177
412019	5208623	8	300	1100	700	52740	9	465786
411952	5209742	7	1300	1700	1500	27970	9	246193
411898	5209746	7	1100	1300	1200	33153	8	276501

UTM Easting	UTM Northing	Mean Elevation (m)	Min Age	Max Age	Centroid Age	Area (m ²)	Average Thickness (m)	Volume (m ³)
411843	5209803	6	300	1100	700	19105	7	127473
412510	5209390	5	1700	2500	2100	417901	7	2848439
412855	5209590	4	2500	2800	2650	61601	6	399397
411420	5208747	6	0	300	150	2231262	6	13527582
411611	5209851	6	0	300	150	239133	6	1459675
413417	5210090	4	2800	3200	3000	247520	7	1688018
411839	5210428	6	1100	1300	1200	37132	8	285247
412007	5211666	6	0	300	150	1046323	6	6353326
411375	5214509	5	300	1300	800	924567	6	5757444
411339	5213833	5	300	1100	700	910687	6	5262776
411028	5213289	5	0	300	150	4613785	6	25786077
410762	5218132	5	300	1100	700	78792	6	477285
410892	5218136	5	300	1300	800	127313	6	757800
410506	5218139	5	0	300	150	321968	5	1769833
410876	5218575	3	0	300	150	18260	3	60739
410776	5218781	3	300	1100	700	99058	4	362656
410360	5219608	4	0	300	150	968892	5	4495125
408013	5231961	5	0	300	150	260280	5	1371290

Appendix E Centroids

UTM Easting	UTM Northing	Distance to Source (km)	Distance to Shoreline (km)	Thickness (m)	Centroid Age (yr)
429624	5095105	28.92	1.57	7.6	3750
429489	5097304	26.80	1.36	9.7	3000
429665	5097482	26.69	1.53	8.7	3600
429793	5097307	26.90	1.66	9.6	4350
428249	5097565	26.15	0.12	11.6	150
428380	5097526	26.23	0.25	16.1	700
428534	5097558	26.24	0.41	15.0	1200
428740	5097545	26.32	0.61	11.0	1500
428980	5097553	26.39	0.85	9.0	2100
429278	5097514	26.53	1.15	8.8	2650
428372	5099084	24.75	0.26	12.3	700
428229	5099165	24.62	0.12	12.1	150
428515	5099137	24.74	0.41	17.8	1200
428701	5099122	24.82	0.59	12.8	1500
428927	5099192	24.83	0.82	9.6	2100
429252	5099082	25.05	1.14	11.6	2650
429447	5099289	24.92	1.35	10.3	3000
429686	5099150	25.14	1.57	10.3	3600
429892	5099391	25.00	1.80	11.3	4350
427869	5102930	20.96	0.11	11.8	150
427912	5104559	19.47	0.44	11.4	700
428430	5100885	23.07	0.46	17.9	1200
428112	5104742	19.38	0.67	15.2	1500
429209	5102333	22.02	1.34	11.5	3000
428608	5102665	21.48	0.79	12.2	2100
428798	5103988	20.35	1.20	16.8	2650
429312	5103450	21.05	1.62	12.9	3600
429500	5103151	21.40	1.75	11.9	4350
427949	5105969	18.19	0.78	16.1	1500
427100	5107067	16.84	0.23	10.0	150
427339	5107161	16.85	0.47	14.5	700
427489	5107388	16.71	0.67	18.3	1400
427900	5107265	17.00	1.04	14.2	2100
428234	5107156	17.25	1.34	17.5	2650
428471	5107024	17.48	1.54	11.4	3000
428731	5106190	18.34	1.59	13.2	3600
428419	5108039	16.56	1.75	13.6	4350

UTM Easting	UTM Northing	Distance to Source (km)	Distance to Shoreline (km)	Thickness (m)	Centroid Age (yr)
427439	5109061	15.19	1.13	14.7	2100
427020	5109042	15.02	0.73	20.4	1400
426513	5109057	14.79	0.25	10.3	150
426786	5109083	14.88	0.52	10.6	700
427788	5109096	15.33	1.48	17.1	2650
427971	5109133	15.39	1.66	11.5	3000
428065	5109170	15.40	1.76	11.0	3600
428207	5109133	15.51	1.87	16.2	4350
428239	5113819	11.74	3.47	9.9	4350
428395	5114636	11.26	3.90	9.2	3600
428220	5115393	10.62	4.01	6.9	3000
425929	5115885	8.66	2.06	10.7	2650
426200	5112911	11.24	1.25	10.0	2100
426499	5110972	13.07	0.86	14.4	1400
424921	5115165	8.65	0.86	9.5	700
423907	5116499	6.98	0.47	5.6	150
417826	5176367	53.95	0.14	6.0	1200
417220	5176851	54.46	0.43	5.5	700
416725	5177130	54.77	0.29	4.5	150
417866	5177033	54.61	0.79	6.2	1500
420580	5153262	30.78	1.88	9.5	3600
418892	5156253	33.80	0.24	6.6	150
419189	5156202	33.74	0.54	13.5	700
419434	5156189	33.72	0.79	7.9	1200
420870	5156285	33.81	2.21	7.1	3600
420693	5156357	33.88	2.04	7.9	3000
420509	5156223	33.74	1.85	9.9	2650
419886	5156233	33.76	1.23	7.3	1500
420261	5156333	33.85	1.60	8.1	2100
421248	5157503	35.04	2.71	6.5	3600
419219	5158386	35.92	0.74	12.5	700
419440	5158461	35.99	0.96	8.3	1200
419852	5158457	35.98	1.37	6.6	1500
420315	5158532	36.05	1.84	7.4	2100
418818	5158438	35.99	0.34	6.4	150
420678	5158657	36.18	2.21	7.3	2650
421096	5158519	36.05	2.62	6.5	3000
421125	5159969	37.50	2.74	7.4	3000

UTM Easting	UTM Northing	Distance to Source (km)	Distance to Shoreline (km)	Thickness (m)	Centroid Age (yr)
420926	5160077	37.60	2.55	6.8	2650
420476	5160475	38.00	2.13	6.3	2100
420007	5160583	38.10	1.67	5.9	1500
419737	5161130	38.66	1.43	7.5	1200
419512	5161657	39.19	1.24	9.9	700
418755	5163514	41.06	0.56	4.8	150
412077	5201359	79.31	1.38	4.8	150
412701	5202602	80.48	1.91	7.2	700
412432	5204738	82.64	1.57	6.1	1200
412831	5203512	81.38	2.01	5.5	1500
413221	5202728	80.56	2.42	7.0	2100
413197	5203905	81.74	2.34	7.8	2650
413135	5204910	82.74	2.27	7.4	3000
411531	5206127	84.11	0.65	5.6	150
412198	5206183	84.10	1.31	7.8	700
412291	5206184	84.09	1.40	7.6	1200
412480	5206143	84.03	1.59	6.4	1500
412698	5206152	84.02	1.81	7.6	2100
412815	5206191	84.05	1.92	8.2	2650
412865	5206172	84.02	1.97	8.2	3000
412707	5206908	84.77	1.78	8.0	3000
412656	5206928	84.80	1.73	7.9	2650
412550	5206931	84.81	1.63	7.3	2100
412383	5206930	84.82	1.46	6.5	1500
412227	5206932	84.84	1.30	7.9	1200
411500	5206920	84.90	0.58	5.9	150
412127	5206944	84.86	1.20	8.3	700
412591	5207409	85.28	1.67	7.6	3000
412555	5207396	85.27	1.63	7.6	2650
412442	5207464	85.35	1.52	7.6	2100
412324	5207419	85.31	1.41	6.8	1500
412144	5207466	85.38	1.22	6.6	700
412214	5207464	85.37	1.29	7.2	1200
411510	5207486	85.46	0.59	6.1	150
412579	5208994	86.86	1.67	6.4	3000
412444	5207962	85.84	1.53	6.5	2650
412281	5208649	86.54	1.39	7.9	2100
412106	5208619	86.53	1.22	8.1	1500

UTM Easting	UTM Northing	Distance to Source (km)	Distance to Shoreline (km)	Thickness (m)	Centroid Age (yr)
411988	5209100	87.02	1.09	8.6	1200
412019	5208623	86.54	1.14	8.8	700
411952	5209742	87.66	1.07	8.8	1500
411898	5209746	87.67	1.02	8.3	1200
411843	5209803	87.73	0.98	6.7	700
412510	5209390	87.26	1.60	6.8	2100
412855	5209590	87.43	1.95	6.5	2650
411420	5208747	86.73	0.53	6.1	150
411611	5209851	87.80	0.75	6.1	150
413417	5210090	87.88	2.56	6.8	3000
411839	5210428	88.36	1.00	7.7	1200
412007	5211666	89.57	1.20	6.1	150
411375	5214509	92.46	0.73	6.2	800
411339	5213833	91.79	0.62	5.8	700
411028	5213289	91.28	0.29	5.6	150
410762	5218132	96.13	0.45	6.1	700
410892	5218136	96.12	0.58	6.0	800
410506	5218139	96.16	0.20	5.5	150
410876	5218575	96.56	0.62	3.3	150
410776	5218781	96.77	0.55	3.7	700
410360	5219608	97.64	0.23	4.6	150
408013	5231961	110.17	0.05	5.3	150
418404	5176922	54.48	0.86	6.4	2100
418724	5176983	54.53	1.08	7.9	2650
418405	5178883	56.44	2.21	8.3	2650
418034	5178786	56.35	1.83	6.7	2100
417608	5178703	56.29	1.40	6.3	1500
417301	5178564	56.17	1.10	7.7	1200
417200	5178200	55.81	1.05	7.8	700
416677	5178795	56.43	0.48	5.9	150
417991	5181385	58.95	1.81	8.6	2650
417648	5181340	58.92	1.46	7.5	2100
416566	5181376	59.02	0.38	6.2	150
417364	5181375	58.97	1.18	6.6	1500
416839	5182546	60.17	0.68	9.0	700
417105	5181530	59.14	0.92	6.5	1200
416520	5184544	62.18	0.55	7.2	700
416709	5184333	61.96	0.72	6.3	1200

UTM Easting	UTM Northing	Distance to Source (km)	Distance to Shoreline (km)	Thickness (m)	Centroid Age (yr)
416223	5184403	62.06	0.24	6.1	150
416889	5184399	62.01	0.91	6.4	1500
417077	5184371	61.98	1.09	7.2	2100
417283	5184711	62.31	1.31	8.2	2650
416660	5187532	65.16	1.14	8.4	2650
416158	5187972	65.62	0.72	7.0	1500
416243	5188454	66.10	0.89	7.4	2100
415807	5188131	65.81	0.40	8.2	700
415901	5188424	66.09	0.55	7.1	1200
415590	5187978	65.67	0.16	6.4	150
415326	5191308	69.01	0.73	7.6	1200
415152	5191369	69.08	0.57	9.2	700
414828	5191395	69.13	0.27	6.0	150
416025	5190703	68.36	1.25	12.5	2650
415542	5191483	69.17	0.98	6.6	1500
415787	5191281	68.95	1.17	7.7	2100
415958	5193256	70.91	1.81	7.2	2650
415875	5193266	70.93	1.74	6.0	2100
416657	5193802	71.42	2.62	3.6	1200
415633	5193380	71.05	1.52	5.2	1500
416768	5193936	71.55	2.75	2.7	700
415301	5193412	71.11	1.21	6.6	1200
415827	5194368	72.03	1.90	4.7	700
414832	5194420	72.15	0.94	4.6	150
418649	5131069	8.75	0.83	7.1	1500
418585	5130970	8.66	0.78	7.8	1200
418528	5130994	8.70	0.72	7.5	700
418158	5131021	8.81	0.35	6.1	150
419347	5130961	8.54	1.53	9.7	4350
419047	5131078	8.69	1.21	8.6	3600
418733	5131021	8.69	0.93	7.8	2100
418858	5131225	8.87	1.01	9.0	2850
419813	5133034	10.57	1.76	9.8	4350
420266	5132403	9.92	2.29	9.3	4850
419546	5132592	10.14	1.55	8.6	3600
419386	5132827	10.39	1.35	8.3	3000
419445	5133878	11.43	1.34	7.9	2650
419177	5133650	11.23	1.10	7.6	2100

UTM Easting	UTM Northing	Distance to Source (km)	Distance to Shoreline (km)	Thickness (m)	Centroid Age (yr)
418954	5133130	10.74	0.90	7.5	1500
418895	5133782	11.39	0.81	7.3	1200
418714	5133350	10.99	0.66	8.1	700
418363	5133342	11.04	0.31	6.5	150
420648	5136414	13.94	2.38	9.3	4850
420281	5136540	14.06	2.00	10.9	4350
420110	5136368	13.89	1.85	8.6	3600
419975	5136579	14.10	1.69	8.1	3000
419821	5136457	13.99	1.55	8.8	2650
419541	5136414	13.96	1.28	7.1	2100
419363	5136680	14.23	1.08	7.4	1500
418896	5136472	14.06	0.64	8.8	700
419115	5136486	14.06	0.85	7.3	1200
418566	5136453	14.08	0.32	6.9	150
419492	5138019	15.56	1.09	6.9	1500
419216	5137996	15.56	0.82	7.3	1200
418984	5138004	15.58	0.59	7.5	700
418674	5138001	15.61	0.28	7.1	150
419686	5137981	15.51	1.29	7.2	2100
420813	5138019	15.55	2.40	9.5	4850
420431	5138049	15.57	2.02	10.8	4350
420287	5138029	15.55	1.88	9.5	3600
420138	5138025	15.55	1.73	8.1	3000
419958	5138043	15.57	1.55	8.7	2650
421068	5140914	18.45	2.55	10.2	4850
420659	5140814	18.34	2.14	11.6	4350
420478	5141110	18.63	1.94	10.0	3600
420266	5140886	18.41	1.75	9.1	3000
420091	5140716	18.24	1.57	8.9	2650
419822	5141113	18.64	1.29	7.8	2100
419525	5141164	18.70	0.99	8.2	1500
419268	5140610	18.16	0.76	7.6	1200
419089	5141295	18.86	0.55	8.0	700
418772	5140810	18.40	0.25	7.3	150
420851	5145039	22.57	2.18	11.3	4350
420595	5144690	22.21	1.93	10.2	3600
420375	5144766	22.29	1.70	9.8	3000
420262	5144659	22.18	1.60	9.7	2650

UTM Easting	UTM Northing	Distance to Source (km)	Distance to Shoreline (km)	Thickness (m)	Centroid Age (yr)
419974	5144880	22.40	1.31	8.1	2100
419557	5144955	22.49	0.89	8.0	1500
419091	5144747	22.30	0.42	8.7	700
419249	5144880	22.43	0.58	8.9	1200
418857	5144889	22.46	0.19	7.5	150
420813	5147922	25.45	2.10	9.8	4350
420480	5149208	26.73	1.72	9.7	3600
420254	5149070	26.59	1.50	11.5	3000
420046	5150395	27.92	1.32	10.3	2650
419891	5148793	26.32	1.15	8.9	2100
419457	5148869	26.40	0.71	8.6	1500
419208	5148313	25.86	0.50	9.9	1200
419062	5150356	27.90	0.34	8.0	700
418888	5148843	26.40	0.14	7.5	150
419013	5152046	29.60	0.30	6.8	700
419301	5153811	31.35	0.62	9.2	1200
418868	5153702	31.26	0.18	6.8	150
419666	5153739	31.27	0.98	7.9	1500
419676	5152153	29.68	0.96	9.0	2100
420129	5153489	31.01	1.44	9.3	2650
420352	5153779	31.30	1.67	9.8	3000

Appendix F Accretion Values

UTM Easting	UTM Northing	accretion (km ³ /yr)	accretion time (years)
429624	5095105	4.48	1900
429489	5097304	6.56	400
429665	5097482	3.34	800
429793	5097307	1.79	700
428249	5097565	14.61	300
428380	5097526	1.16	800
428534	5097558	34.16	200
428740	5097545	6.32	400
428980	5097553	6.69	800
429278	5097514	13.49	300
428372	5099084	0.55	800
428229	5099165	15.15	300
428515	5099137	34.03	200
428701	5099122	5.28	400
428927	5099192	6.48	800
429252	5099082	17.92	300
429447	5099289	6.80	400
429686	5099150	6.87	800
429892	5099391	1.82	700
427869	5102930	72.93	300
427912	5104559	4.91	800
428430	5100885	87.28	200
428112	5104742	23.38	400
429209	5102333	36.90	400
428608	5102665	34.25	800
428798	5103988	78.03	300
429312	5103450	21.29	800
429500	5103151	10.54	700
429278	5105393	2.57	300
427949	5105969	5.49	400
427100	5107067	51.69	300
427339	5107161	2.55	800
427489	5107388	33.45	600
427900	5107265	18.64	800
428234	5107156	50.48	300
428471	5107024	9.63	400
428731	5106190	4.00	800
428419	5108039	13.52	700

UTM Easting	UTM Northing	accretion (km ³ /yr)	accretion time (years)
427439	5109061	4.73	800
427020	5109042	9.28	600
426513	5109057	12.85	300
426786	5109083	0.48	800
427788	5109096	12.36	300
427971	5109133	1.59	400
428065	5109170	1.24	800
428207	5109133	2.78	700
428484	5108841	22.00	300
428161	5110625	29.45	300
428239	5113819	20.74	700
428395	5114636	26.52	800
428220	5115393	75.47	400
425929	5115885	224.48	300
426200	5112911	38.49	800
426499	5110972	62.11	600
424921	5115165	17.21	800
423907	5116499	197.68	300
417826	5176367	13.03	200
417220	5176851	1.58	800
416725	5177130	10.07	300
417866	5177033	13.76	400
418404	5176922	4.70	800
418034	5178786	6.85	800
417608	5178703	20.67	400
417301	5178564	11.32	200
417200	5178200	2.09	800
416677	5178795	48.85	300
417648	5181340	6.19	800
416566	5181376	44.27	300
417364	5181375	14.68	400
416839	5182546	2.84	800
417105	5181530	15.29	200
416520	5184544	4.05	800
416709	5184333	16.37	200
416223	5184403	33.43	300
416889	5184399	11.34	400
417077	5184371	4.18	800
416660	5187532	25.44	300

UTM Easting	UTM Northing	accretion (km ³ /yr)	accretion time (years)
416158	5187972	9.91	400
416243	5188454	7.51	800
415807	5188131	5.46	800
415901	5188424	24.39	200
415590	5187978	32.29	300
415326	5191308	23.83	200
415152	5191369	2.39	800
414828	5191395	27.19	300
416025	5190703	8.39	300
415542	5191483	9.52	400
415787	5191281	5.25	800
415958	5193256	3.26	300
415875	5193266	0.91	800
416657	5193802	0.31	200
415633	5193380	9.89	400
416768	5193936	0.27	800
415301	5193412	23.65	200
415827	5194368	4.78	800
414832	5194420	62.82	300
418649	5131069	0.29	400
418585	5130970	1.86	200
418528	5130994	0.25	800
418158	5131021	7.90	300
419347	5130961	4.27	700
419047	5131078	3.73	800
418733	5131021	1.07	800
418858	5131225	0.32	700
419813	5133034	9.32	700
420266	5132403	158.93	300
419546	5132592	10.29	800
419386	5132827	10.02	400
419445	5133878	14.18	300
419177	5133650	10.40	800
418954	5133130	2.79	400
418895	5133782	32.92	200
418714	5133350	2.23	800
418363	5133342	57.70	300
420648	5136414	45.25	300
420281	5136540	1.93	700

UTM Easting	UTM Northing	accretion (km ³ /yr)	accretion time (years)
420110	5136368	5.54	800
419975	5136579	2.96	400
419821	5136457	12.72	300
419541	5136414	6.36	800
419363	5136680	2.33	400
418896	5136472	0.88	800
419115	5136486	30.18	200
418566	5136453	29.44	300
419492	5138019	2.11	400
419216	5137996	15.76	200
418984	5138004	0.38	800
418674	5138001	13.82	300
419686	5137981	2.54	800
420813	5138019	24.06	300
420431	5138049	1.55	700
420287	5138029	2.55	800
420138	5138025	2.37	400
419958	5138043	8.26	300
421068	5140914	111.07	300
420659	5140814	6.89	700
420478	5141110	17.42	800
420266	5140886	10.70	400
420091	5140716	32.39	300
419822	5141113	15.45	800
419525	5141164	24.04	400
419268	5140610	49.17	200
419089	5141295	5.24	800
418772	5140810	60.44	300
420851	5145039	6.68	700
420595	5144690	14.57	800
420375	5144766	6.05	400
420262	5144659	14.07	300
419974	5144880	14.66	800
419557	5144955	23.25	400
419091	5144747	2.73	800
419249	5144880	32.72	200
418857	5144889	29.98	300
420813	5147922	21.91	700
420480	5149208	21.99	800

UTM Easting	UTM Northing	accretion (km ³ /yr)	accretion time (years)
420254	5149070	14.63	400
420046	5150395	21.24	300
419891	5148793	23.83	800
419457	5148869	46.36	400
419208	5148313	27.14	200
419062	5150356	3.80	800
418888	5148843	42.46	300
419013	5152046	1.17	800
419301	5153811	72.52	200
418868	5153702	32.05	300
419666	5153739	25.57	400
419676	5152153	8.10	800
420129	5153489	41.58	300
420352	5153779	8.13	400
420580	5153262	22.79	800
421071	5153312	26.67	700
418892	5156253	17.50	300
419189	5156202	1.24	800
421206	5156300	6.51	700
419434	5156189	25.69	200
420870	5156285	2.48	800
420693	5156357	4.16	400
420509	5156223	9.38	300
419886	5156233	11.94	400
420261	5156333	4.13	800
421300	5157106	1.13	700
421248	5157503	3.21	800
419219	5158386	4.39	800
419440	5158461	43.32	200
419852	5158457	22.54	400
420315	5158532	12.20	800
418818	5158438	44.05	300
420678	5158657	16.88	300
421096	5158519	26.73	400
421125	5159969	0.43	400
420926	5160077	2.75	300
420476	5160475	6.29	800
420007	5160583	7.38	400
419737	5161130	48.49	200

UTM Easting	UTM Northing	accretion (km ³ /yr)	accretion time (years)
419512	5161657	5.30	800
418755	5163514	147.73	300
412077	5201359	271.37	300
412701	5202602	2.32	800
412432	5204738	5.30	200
412831	5203512	22.26	400
413221	5202728	7.35	800
413197	5203905	22.22	300
413135	5204910	1.21	400
411531	5206127	23.86	300
412198	5206183	0.57	800
412291	5206184	4.86	200
412480	5206143	3.87	400
412698	5206152	1.86	800
412815	5206191	1.46	300
412865	5206172	0.79	400
412707	5206908	0.32	400
412656	5206928	0.75	300
412550	5206931	0.72	800
412383	5206930	1.57	400
412227	5206932	2.81	200
411500	5206920	13.16	300
412127	5206944	0.38	800
412591	5207409	0.35	400
412555	5207396	0.57	300
412442	5207464	0.73	800
412324	5207419	0.91	400
412144	5207466	0.15	800
412214	5207464	2.01	200
411510	5207486	13.60	300
412579	5208994	0.83	400
412444	5207962	1.11	300
412281	5208649	4.46	800
412106	5208619	1.82	400
411988	5209100	3.44	200
412019	5208623	0.58	800
411952	5209742	0.62	400
411898	5209746	1.38	200
411843	5209803	0.16	800

UTM Easting	UTM Northing	accretion (km ³ /yr)	accretion time (years)
412510	5209390	3.56	800
412855	5209590	1.33	300
411420	5208747	45.09	300
411611	5209851	4.87	300
413417	5210090	4.22	400
411839	5210428	1.43	200
411339	5213833	6.58	800
411028	5213289	85.95	300
410762	5218132	0.60	800
410506	5218139	5.90	300
410776	5218781	0.45	800
410360	5219608	14.98	300
408013	5231961	4.57	300