Newfoundland Labrador

Natural Resources

Mines

COASTAL EROSION IN ST. GEORGE'S BAY, WESTERN NEWFOUNDLAND

M. Irvine

Open File 012B/0705

St. John's, Newfoundland
August, 2019

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NOTE

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Cover photo: View looking northeast, unconsolidated bluffs, St. David's, western Newfoundland.

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ABSTRACT

The coast of St. George's Bay, western Newfoundland, is vulnerable to erosion as shown by results from field studies conducted by the Geological Survey of Newfoundland and Labrador (GSNL) between 2011 and 2016, and earlier by the Geological Survey of Canada (GSC) between 1991 and 2000. Real Time Kinematic (RTK) topographic survey data were collected by the GSC between 1994 and 2000 at five monitoring sites, and RTK and Unmanned Aerial Vehicle (UAV) data were collected by GSNL between 2011 and 2016 at ten monitoring sites.

Coastal erosion monitoring quantify rates of coastal erosion of the cliffs and changes in beach profiles, assess the longer term effects of climate change, and determine factors affecting the variable rates of coastal erosion. Planners, landowners and other stakeholders can use the published results allowing for better land-use management practices.

The mean annual rate of erosion at St. David's is 59 cm, and 2 cm a year at Port au Port. Beach width and cliff exposure to waves appear to be the dominant factors resulting in higher rates of erosion, and where waves do not regularly reach the cliff base, groundwater flow is likely having the most impact. Changes in the climate will affect coastal erosion along the coastline of St. George's Bay. Factors such as rising sea levels, and increases in the frequency and severity of storms will intensify wave erosion at the base of cliffs.

This research is part of a systematic, long-term study of coastal environments around Newfoundland and Labrador. Repeated UAV surveys are planned at existing monitoring sites. Data analysis will allow for a better determination of coastal erosion and an assessment of geomorphic variables affecting coastal erosion.

INTRODUCTION

This report describes the current knowledge, and the factors influencing coastal *erosion** in St. George's Bay, western Newfoundland. A monitoring program initiated in 1991 by the Geological Survey of Canada (GSC), following earlier work by Forbes (1984), conducted ground surveys and a photogrammetric study (Forbes *et al.*, 1995) of the area. Since 2011, the Geological Survey of Newfoundland and Labrador (GSNL) has expanded on the original program and conducted repeated monitoring (using ground and aerial surveys) at ten sites. This is part of a long-term, systematic, province-wide coastal monitoring initiative providing information on coastal change, and associated hazards to communities and stakeholders.

Coasts are dynamic environments that present a variety of challenges for planning, safety and infrastructure. As about 90% of the province's population live and work in coastal communities, the determination of current and future landscape changes is integral in making constructive land-use decisions. Coastal erosion, *slope movement* and flooding affect communities and consequent damage to roads, trails, cabins, wharfs, breakwaters, and houses require costly repairs (Plate 1; Batterson *et al.*, 1995, 1999; Liverman *et al.*, 2001, 2003).

Assessments of coastal change will help decrease the vulnerability of infrastructure and minimize property damage. *Coastal setbacks* should take into consideration rates of coastal erosion and future environmental conditions, including climate change and rising sea levels (Sanò *et al.*, 2011). For example, jurisdictions such as North Carolina and Rhode Island are using rates of coastal erosion, and the size and type of structures, when calculating setback requirements; in areas with more rapid erosion, the setback distance is greater than in more stable areas (Randall and deBoer, 2012; North Carolina Department of Environmental Quality, 2016). Coastal setback limits vary in Canada. In Québec, some municipali-

Plate 1. *Coastal processes impacting infrastructure. A) During a landslide in Daniel's Harbour in 2013, a large amount of unconsolidated sediment was moved from the slope and deposited on the beach; the old highway was damaged and pipes were exposed; B) Coastal erosion along the top of a cliff in Conception Bay South resulted in the closure of a walking trail within a few years of being constructed. Quantifying rates of erosion is crucial to determine setback values in order to reduce the risk of this; C) Coastal cliff, Point Verde, 1995. Coastal erosion along the top of a cliff has undermined an old cement structure; D) Same portion of the coastal cliff at Point Verde at 1C, taken in 2005. Note the amount of erosion that had occurred at the base of the structure over a ten-year period. Continued erosion, at a rate of 45 cm a year, caused the concrete structure in the photo to fall to the base of the cliff in 2011.*

*A glossary of terms used in this open-file report is given in Appendix A; these are italicized on first usage in the text.

ties apply a 10–15 m setback independent of erosion rates; others are employing a more restrictive setback based on rates of erosion. In Prince Edward Island, the setback limit is 22.9 m, or 60 times the annual rate of erosion, whichever is greater, for new infrastructure (DV8 Consulting, 2016).

In Newfoundland and Labrador, the 'policy for development in shore water zones' (Department of Environment and Conservation (DEC), 2016a) ensures development in the shore water zone minimizes potential economic losses and negative impacts on water quality, water quantity and habitats. The shore water zone consists of the area between the low- and high-water marks, and incorporates areas potentially inundated by maximum waves, *storm surges* and maximum anticipated sea levels for a 1:100 year design. The DEC states that infilling, drainage, dredging, channelization and removal of surface vegetation, which could impact the environment, is not permitted, as well as extensive paving of surfaces and the discharge of sewage and other waste. Other developments may require written permission or the implementation of mitigation measures. A 15-m buffer, measured from the high-water mark, is required to protect the water resources, unless a specific setback is required (DEC, 2016b). Managing and modifying human activities, in ways appropriate for local coastal environments, have the potential to ensure that they are utilized in a sustainable manner.

OBJECTIVES

The scope of the monitoring program consists of the following:

1) Quantify rates of coastal erosion and changes in beach morphology,
2) Determine *geomorphic* variables (cliff and beach composition, vegetation, beach width, *fetch*, *longshore drift*) that affect coastal change,
3) Assess how the physical environment will be impacted by *climate* change and sea-level rise, and
4) Identify areas most susceptible to the changes indicated in the first three points.

REVIEW

St. George's Bay is a triangular indentation exposed to the west and southwest (Figure 1). The study area includes

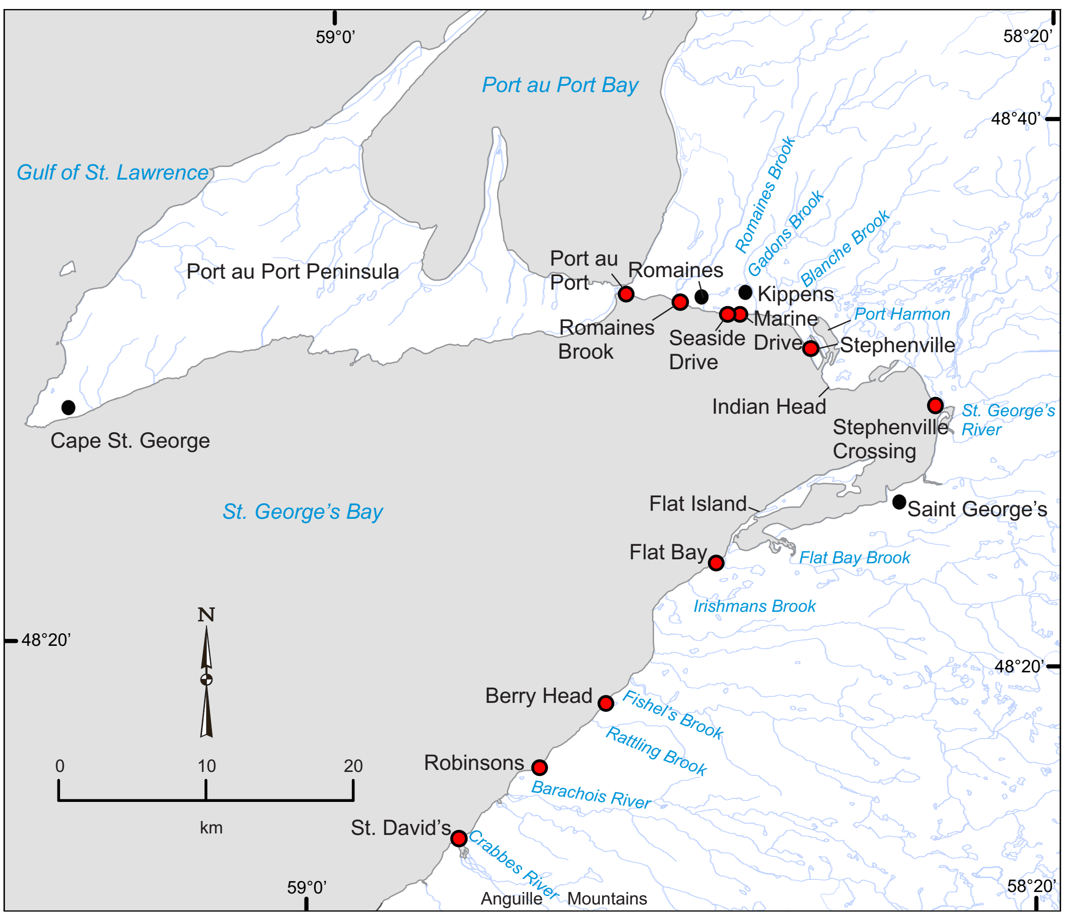


Figure 1. *Map showing St. George's Bay area. Red dots are monitoring sites, and black dots are town locations.*

Port au Port, Kippens, Stephenville, Stephenville Crossing, Robinsons, and St. David's. Roads and houses have been built within 100 m of the coastline (essentially clifftops), and new construction and infrastructure are currently being built less than 50 m from the clifftop in areas prone to coastal erosion (Plate 2).

Western Newfoundland was glaciated during the late *Wisconsinan*. The coastline between Port au Port and the Anguille Mountains is dominated by *gravel*, *sand*, *silt* and *clay* deposited during, and after, the late Wisconsinan glaciation (Batterson and Sheppard, 2000; Bell *et al.*, 2003; Plate 3A, B). Between Port au Port and Romaines Brook, sediment settled where the glacier terminated in the ocean, whereas sediment east of Romaines Brook was deposited farther from the ice-front in *glaciofluvial* deltas (Batterson and Janes, 1997). The southeastern shore of St. George's Bay, between Flat Bay and St. David's, is about 28 km long; the cliffs are *basal till*, overlain by silt, clay and *glaciomarine* sand capped by gravel glaciofluvial outwash (Plate 3B; Bell *et al.*, 1999, 2001; Liverman and Sheppard, 1999; Liverman, 2001). The cliffs, up to 80 m high, are fronted by a gravel, sand and boulder beach, which is 100 m wide at low tide. The beach is continuous, except at the mouths of the rivers (Figure 1).

At the head of St. George's Bay are depositional beach systems: the *barrier beach* at Stephenville is a complex of *Holocene* gravel and sand beach *ridges* breached at its eastern end, whereas the Stephenville Crossing barrier is a sand dune system (Plate 3C); Flat Island is a 12-km-long gravel *spit* (Shaw and Forbes, 1995).

Coastal-change classification and assessments indicate that parts of the St. George's Bay coastline are more vulnerable to erosion than other areas in the province; *e.g.*, areas of thick glacial deposits of which the St. George's Bay cliffs are composed of, and the low elevation of the adjacent barrier beaches. Shaw *et al.* (1998) consider the eastern coastline of St. George's Bay as being highly sensitive to sea-level rise. Apart from the northwest coast of the Burin Peninsula and an area near Musgrave Harbour, the remainder of the island has a low or moderate sensitivity to sea-level rise (Shaw *et al.*, 1998). Using Catto's (2011) classification, most of the sites monitored in this study have moderate, high or extreme sen-

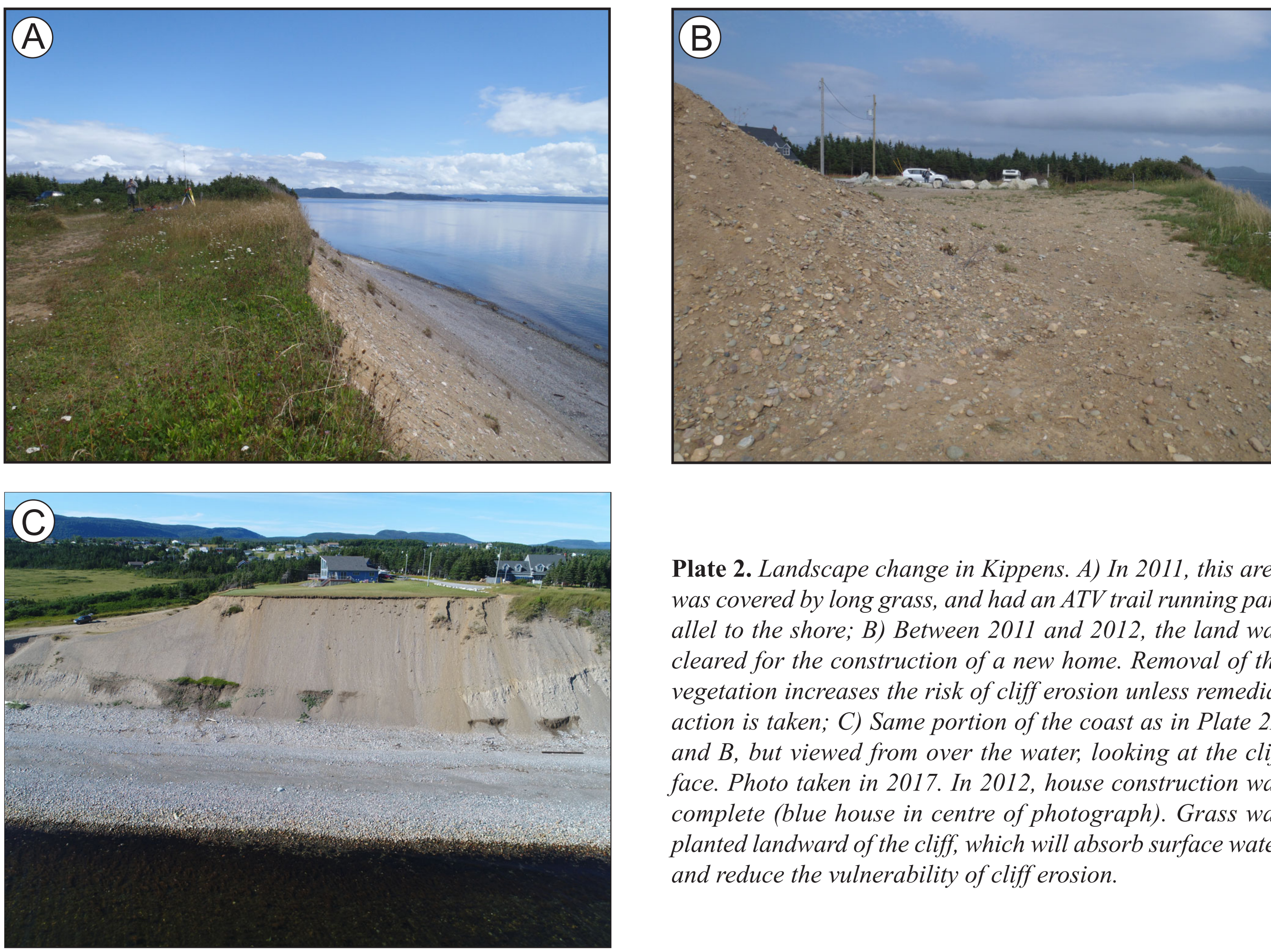


Plate 2. *Landscape change in Kippens. A) In 2011, this area was covered by long grass, and had an ATV trail running parallel to the shore; B) Between 2011 and 2012, the land was cleared for the construction of a new home. Removal of the vegetation increases the risk of cliff erosion unless remedial action is taken; C) Same portion of the coast as in Plate 2A and B, but viewed from over the water, looking at the cliff face. Photo taken in 2017. In 2012, house construction was complete (blue house in centre of photograph). Grass was planted landward of the cliff, which will absorb surface water and reduce the vulnerability of cliff erosion.*

Plate 3. *Examples of coastal environments along St. George's Bay. A) The coast between Port and Port and Stephenville consists primarily of unconsolidated cliffs, although there are variations in sediment composition and vegetation cover. This aerial view, captured in May 2016, shows the general stratigraphy and setting of the coastal cliff east of Romaines Brook. Cliff stratigraphy includes layers of sand and gravel, and silt and clay. The cliff is unvegetated and fronted by a gravel beach. Houses have been built within 100 m of the clifftop; B) Cliff of poorly sorted sand and gravel, fronted by a cobble and boulder beach at Flat Bay; C) Sand dunes at Stephenville Crossing. As the area is low-lying and exposed to the west, it is susceptible to flooding and erosion.*

sitivity designations (Table 1). The cliffs are also susceptible to catastrophic slope failures, such as *retrogressive landslides* (*e.g.*, Romaines Brook) that have resulted in the landward erosion of the clifftop by 60 m (*see* Forbes *et al.*, 1995).

Examples of similar environments to St. George's Bay include New England, USA, where deposits from the Wisconsinan glaciation dominate the coastline, and include cliffs of glaciomarine silt and clay. Erosion of these cliffs varies depending on location, and the most rapid erosion is attributed to wave action along coastlines that have a large fetch. In protected areas, *groundwater* is the most influential agent causing erosion; seepage occurs at the contact of coarse-grained material and less *permeable* material, normally *bedrock*. Erosion by rain or snowmelt also contributes to erosion on unvegetated slopes. Landslides occur most commonly in glaciomarine sediment (that contains fine-grained material), after snowmelt (Kelley, 1999). Coastal cliffs have also formed in late *Pleistocene* glacial and interglacial sediments along portions of the coastline in Puget Sound, Washington, USA; similar to those on the coast of St. George's Bay, the cliffs are composed of sands, gravels, silts and clays. The spatially variable rates of coastal erosion can be attributed to shoreline orientation, beach characteristics and cliff composition; accelerated erosion has occurred on cliffs that have a high wave exposure (National Research Council, 1999).

Table 1. Coastal Erosion Index (CEI) and Coastal Sensitivity Indices (CSI) classifications according to Catto (2011). With the exception of Berry Head and Port au Port, sites were designated as moderate to extreme

Site	CEI	CSI
Berry Head	Low	Low
Flat Bay	Extreme	Moderate
Kippens	Extreme	Moderate
Port au Port	Low	Low
Robinsons	High	Moderate
Romaines Brook	Extreme	Moderate
St. David's	High	Moderate
Stephenville	High	Moderate
Stephenville Crossing	High	High

REPORT STRUCTURE

The following sections describe factors that govern and influence rates of coastal erosion, and provide a general description of the effects of these factors on the coastline of St. George's Bay. The methods used to collect and analyze the data, and the sources of error, are presented. In the Results section, factors influencing coastal erosion for each monitoring site are described and rates of coastal erosion are quantified for sites with sufficient data, incorporating data from the GSC (Forbes *et al.*, 1995), and GSNL reports (Irvine, 2012, 2013, 2014, 2015). The final section discusses factors that influence the spatially variable rates of erosion of the cliffs between Port au Port and St. David's. How and why erosion rates may change are considered.

FACTORS AFFECTING COASTAL EROSION

SEA LEVEL

Glaciers and fluctuating sea levels influence adjacency landscape processes and sediment composition. Postglacial sea-level change varies across Newfoundland and Labrador, and is dependent on the combination of *eustatic* changes (in sea level due to water held in ice sheets and glaciers), and *isostatic* changes (due to the rebound of the crust of the Earth). During the last glaciation, the province was covered by ice that depressed the Earth's crust. The boundaries of the previously glaciated areas were affected by a marginal forebulge, which is an elevated part of the crust. As rising air temperatures melt the ice sheet and the ice margin retreats, the crust rebounds and the forebulge migrates toward the centre of the ice sheet; a process that continues to the present (Quinlan and Beaumont, 1981). Hence, for most of the island, following deglaciation, the sea level was initially higher than at present, fell to below current levels, and then rose again to present-day levels. Exceptions are the Northern Peninsula, where the land shows evidence of continuous emergence (or a continuous fall in sea level) since deglaciation, and the Avalon Peninsula, where sea level has been rising continuously (Liverman, 1994).

For St. George's Bay, after deglaciation, the *marine limit* was about 105 m above present-day level at 14 000 Ka and fell to 25 m below current sea level at 9400 Ka; this was followed by a period of continuous sea-level rise (Bell *et al.*, 2003). The cliff sediments are glaciomarine, and include silt, clay and sand; landforms include sea cliffs and raised deltas (Batterson and Sheppard, 2000; Bell *et al.*, 2001, 2003) indicating that the coastline is below the earlier glaciated marine limit. Sediments dominated by, or, containing fine-grained particles (silt and clay) are typically only deposited in low-energy glaciomarine or glaciolacustrine environments, whereas those deposited in a higher energy glaciofluvial environment typically contain more sand and gravel-sized particles.

By the end of this century, the relative sea level is projected to rise along all of the province's coastlines, with the greatest rise, of over 100 cm, for the Avalon Peninsula (Batterson and Liverman, 2010). For St. George's Bay, projections suggest that sea level will have risen between 90 and 100 cm relative to 1990. More recent projections by James *et al.* (2014, 2015) indicate that projections of median *relative sea level* for Corner Brook are somewhat less than the earlier prediction; *i.e.*, 73 cm between 2081 and 2100, relative to 1986-2005. Higher sea levels will accelerate erosion of the *toe* of *unconsolidated* cliffs, and morphological changes to beaches including erosion and *overwash*, the landward migration of barrier beaches, and the possibility of new beaches forming from material derived from eroding cliffs. The risk associated with storm-surge flooding will increase as sea level rises, resulting in property and infrastructure vulnerability (Lemmen *et al.*, 2016).

Tidal range impacts the landward extent of waves. In a storm event, or when large waves coincide with a high tide, flooding and erosion occurs farther inland. Tidal ranges vary between locations, and shorelines are classified as microtidal (<2 m), mesotidal (2–4 m) or macrotidal (>4 m; Davidson-Arnott, 2010). The tidal range at Stephenville is 1.6 m (Fisheries and Oceans Canada, 2015) and is considered microtidal. Compared to locations with larger tidal ranges, such as the Bay of Fundy, where the tidal range exceeds 12 m, the tidal range in St. George's Bay is less significant than other factors in modifying coastal environments.

Storms (*e.g.*, storm surges) increase vulnerability to erosion and flooding, particularly if they coincide with high tides. Waves overtop beaches and barriers and form *washover fans* (Plate 4), remove sediment from the base of cliffs (Plate 5A), create a *scarp* at the base of a *foredune*, and transport sediment to the *nearshore* (Figure 2; Castelle *et al.*, 2015). A tidal gauge located at Channel-Port aux Basques, 75 km southwest of St. David's is part of the *permanent water level network* collecting storm-surge data. Between 1935 and 2008, the normalized average number of storm-surges, 40 cm above the predicted *astronomical tide*, was 3 every 20 years, and the maximum water-levels during this interval, which occurred in 2000, was 2.27 m above mean high tide (Environment Canada, 2015). If a storm surge occurs during a high tide in St. George's Bay, any terrain below the 3 m asl contour is subject to flooding and direct wave attack.

SITE COMPOSITION AND LANDFORMS

The susceptibility of sediment to erosion is dependent on the grain size, shape and cohesion of the particles. Due to the

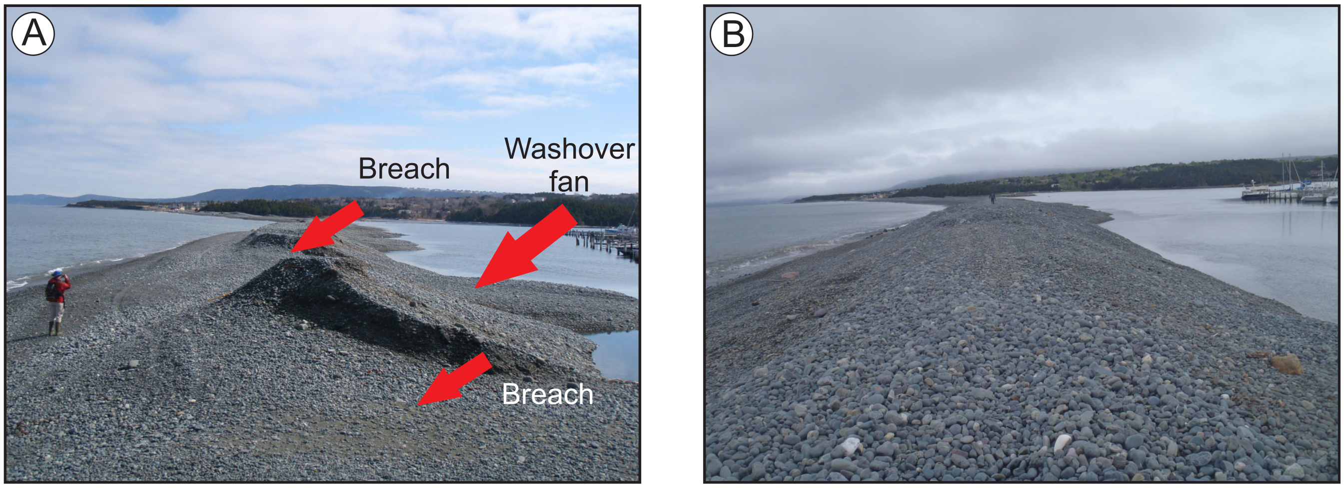


Plate 4. *Impact of a storm surge, Conception Bay South. A) In the spring of 2013, a storm surge occurred during a high tide, and resulted in morphological changes to the barrier near the yacht club at Conception Bay South. Waves breached the barrier, moving sediment from the top and seaward face, forming washover fans and depositing sediment on the landward side of the barrier and in the lagoon; B) As the barrier provides protection from flooding to infrastructure landward, and the channel provides boat access from the lagoon to Conception Bay, sediment was dredged from the lagoon to rebuild the barrier.*

water content and cohesion of clay and silt, sediment containing fine-grained particles are generally more resistant to erosion from wind and water than those containing mostly sand. However, once the finer particles are disturbed or become saturated, *e.g.*, after heavy rains or snowmelt, silt and clay on a cliff may slump as a cohesive unit resulting in significant erosion, whereas sand will be more easily eroded during non-storm conditions. If there are cobbles or boulders in the cliff, they will roll down the cliff after release by erosion, and provide some protection to the fine-grained sediment from the waves.

The coastline between Port au Port and Stephenville, and between Flat Bay and St. David's, is dominated by cliffs of unconsolidated sand, gravel, clay and silt (Forbes *et al.*, 1995; Plate 3A, B) deposited in glaciofluvial, *marine* and *fluvial* environments (Batterson, 2001). Fronting the cliffs is a predominantly gravel and boulder beach. To the east, barrier beaches have formed at Stephenville and Stephenville Crossing. The barrier beach at Stephenville consists of gravel, with sand in the north. There is a sand *dune field* at Stephenville Crossing; the beach has a continuous foredune ridge and a wide dune system covered with grass and shrubs landward (Plate 3C).

CLIMATE AND WEATHER

Wind and water dynamics result in the erosion of unconsolidated cliffs, but sediment composition and vegetation cover also play a part. Surface water generates *sheetwash*, *rills* and *gullies* on unconsolidated slopes, particularly on unvegetated slopes (Plate 5B). *Groundwater* seepage occurs at the contact between different sediment types. On cliffs of low permeability (silt, clay or bedrock), overlain by more permeable units (sand or gravel), groundwater will exit the cliff at the junction of the units, dislocating sediment from the cliff (Plate 5C). Wind abrades sand from a cliff face, and unvegetated slopes are particularly susceptible to this form of erosion (Plate 5D).

The quantity of surface water and groundwater to which the cliffs are exposed varies with precipitation. St. George's Bay, in the western Newfoundland forest ecoregion, receives abundant rainfall, and has high winds especially in the winter months (Government of Canada, 2016; Government of Newfoundland and Labrador, 2017).

Changes in the climate will modify coastal processes. Climate-change projections vary across the globe, and for Newfoundland and Labrador regional projections have been determined based on provincial *weather* station data and regional models (Finnis, 2013). Table 2 outlines the expected changes for the St. George's Bay area, and the potential implications for coastal environments.

VEGETATION

The root systems of the plants increase the shear strength of the soil, bind sediment particles, and remove soil moisture, and vegetation cover intercepts and absorbs rain and reduces the wind exposure to the sediment; these characteristics decrease the amount of material from being destabilized and eroded (Myers, 1993). In coastal dune environments, grass increases the amount of sand being deposited and trapped (Walker and Barrie, 2006; Priestas and Fagherazzi, 2010).

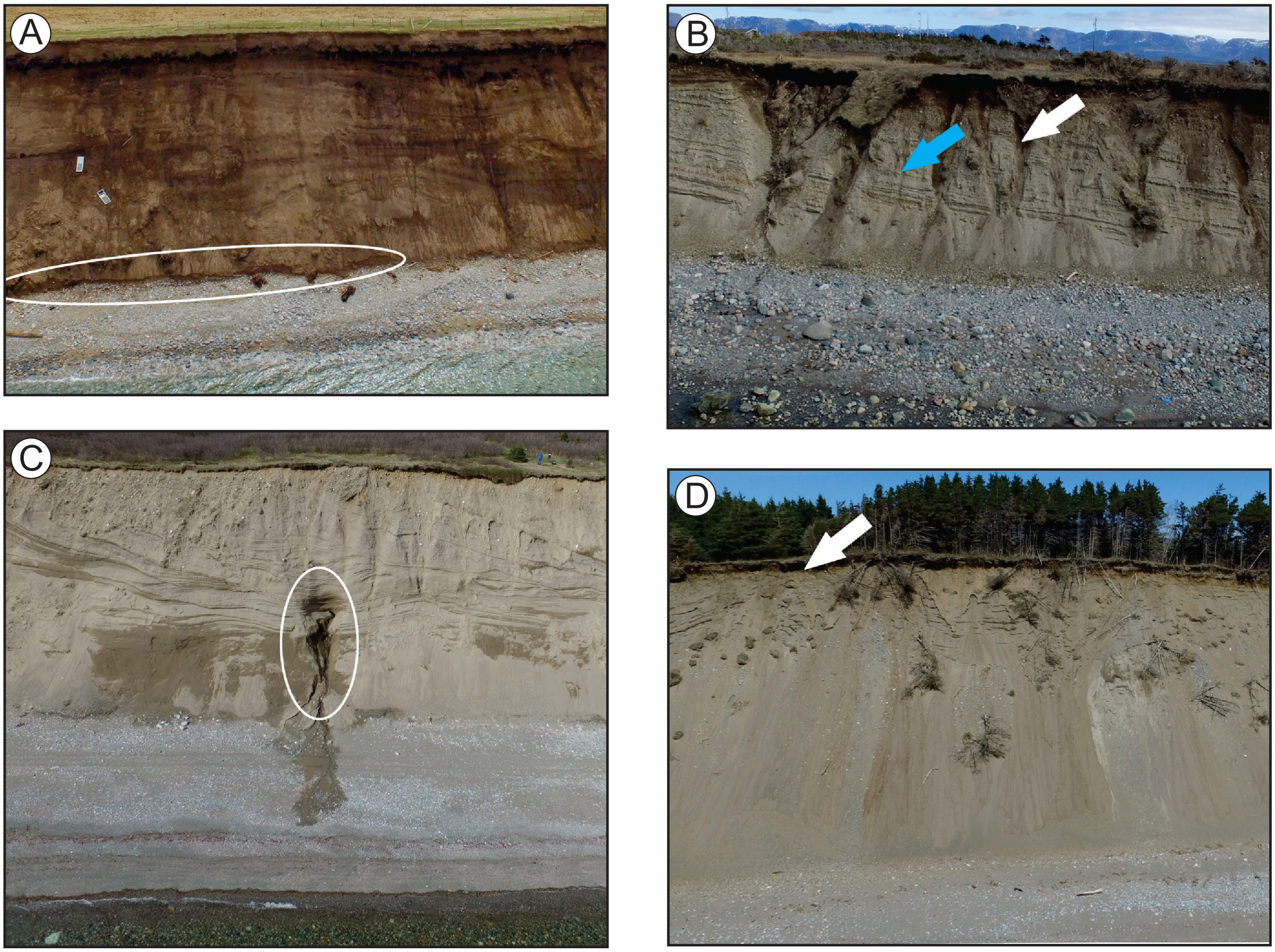


Plate 5. *Erosional agents. A) In exposed areas with a narrow beach backed by a cliff, such as St. David's, waves can remove sediment from the cliff base, forming wave notching (circled); B) Rain and snowmelt result in rills (blue arrow) and gullies (white arrow), moving sediment to the base of the cliff; this is occurring at Parsons Pond; C) Groundwater is an influential agent causing erosion; seepage occurs at the contact of permeable coarse-grained material and non-permeable material. At Marine Drive a spring (circled) has formed at the contact of the sand and gravel layer, which is underlain by silt and clay; D) Wind has blown sand particles off the cliff face, creating overhangs (white arrow).*

Vegetation cover and type vary along the shore of St. George's Bay. Grasses, sedges and shrubs are present along some cliffs (*e.g.*, Berry Head) but not others (*e.g.*, St. David's). Landward, shrubs and grasses typically dominate. The *foreshore* of the gravel beaches and barriers has little to no vegetation, although grasses grow landward of the barrier ridges. Grasses, moss and trees dominate the *backshore* of the dunes at Stephenville Crossing.

MARINE CONDITIONS AND BEACH MORPHODYNAMICS

Dissipative and *reflective* beach states are end-points on the beach continuum, and different beaches, and parts of the same beach, can vary within the continuum and may change over time. The beach is dependent on prevailing wave conditions, sediment characteristics, and tide and wind conditions. Some aspects may also be an inheritance from when these conditions were different, because of the time necessary to equilibrate to the change (Woodroffe, 2002). Waves generated by winds blowing over the ocean, move sediment on, off, and along a beach, and when waves reach the base of a cliff, the water can remove sediment directly, or erode loose material accumulated at the cliff base (Plate 5A). The frequency of wave impacts at the base of cliffs is controlled by weather, fetch (areas with a large fetch have the potential for large, high-energy waves to form), and the width and shape of the beach. A storm surge can increase the water level by 2 m or more. Less intense storms, occurring in rapid succession, can also erode significant quantities of sediment (Lemmen *et al.*,

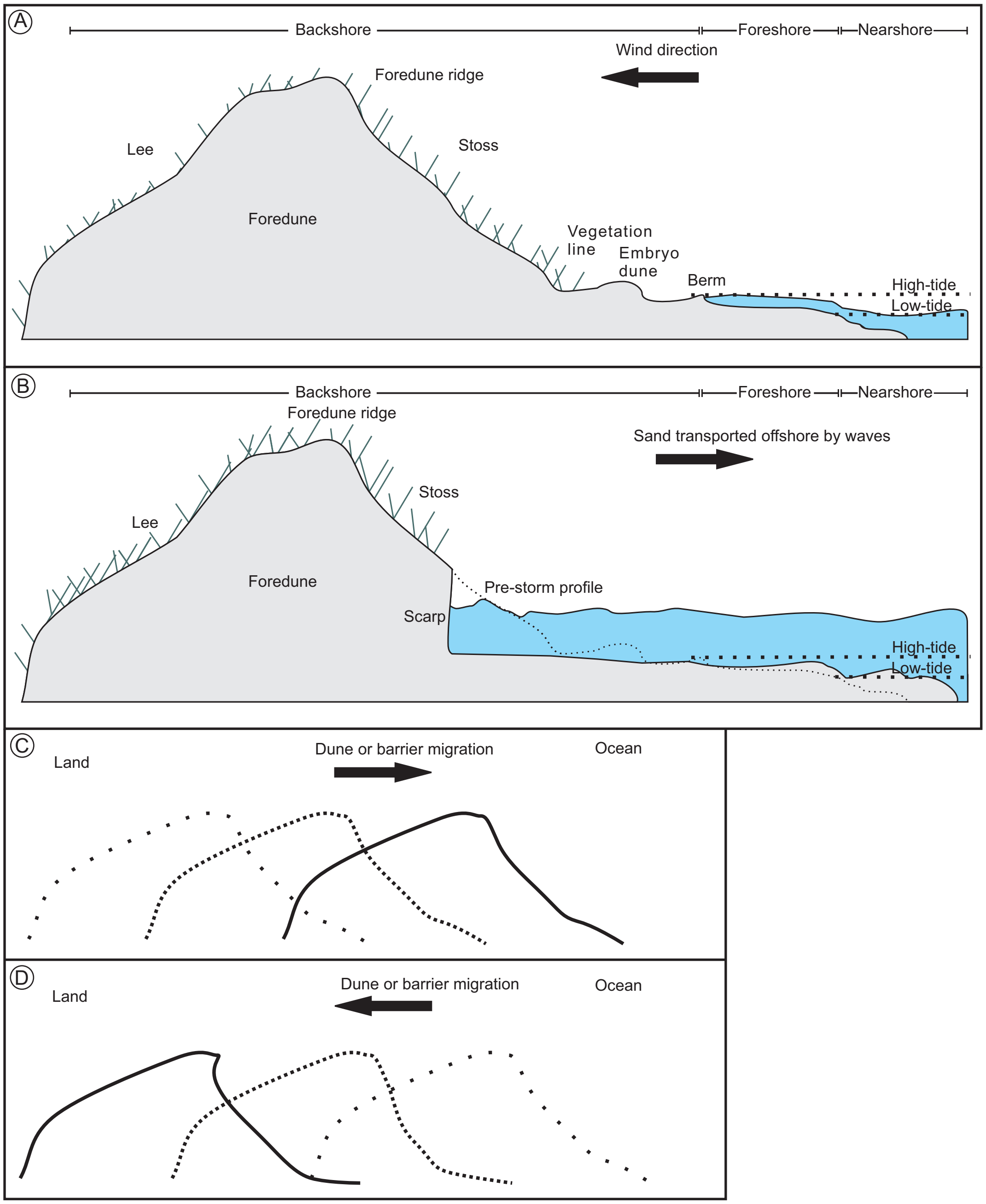


Figure 2. *Sketch profiles of the coastal zone of a beach environment. A) The foredune system, including the backshore, foreshore, nearshore, foredune ridge, vegetation line, embryo dune and berm; B) A storm can result in short-term erosion of the foredune. Large waves will remove sediment from the base of the foredune and create a scarp, and depending on currents and the bathymetry of the ocean floor, sediment is deposited in the nearshore, or in the offshore. Generally, the beach face will flatten, and the berm and the embryo dune (if present) will be eroded. If the waves are large, the foredune will breach and overwashing will occur. After the storm event, if the sediment remains in the nearshore, it is returned onshore to the beach by waves, and the berm can rebuild. Wind can move the sand back to the backshore, resulting in the formation of the embryo dune and dune ramp, and the foredune will rebuild; C) In the long term, accreting or prograding coasts develop when sediment gain exceeds sediment loss (which is termed a 'positive sediment budget'); D) In the long term, on eroding or receding coasts, sediment loss exceeds sediment gain (which is termed a 'negative sediment budget') and the dune system or berm moves landward. This can occur when sand is removed from the dune system or beach system and deposited offshore in environments too deep for the sediment to be returned, when sediment is moved along a shoreline through longshore drift, or when sediment is removed from the system through dredging or other activities.*

Table 2. Predicted changes in the climate conditions and implications for the physical environment

Expected change	Implication
Increase in mean daily precipitation, in particular in the winter (Finnis, 2013)	Increase in soil saturation, snowmelt, surface water and ground water
Intensification of precipitation (Finnis, 2013)	
Increase in precipitation events (Finnis, 2013)	
Increase in the maximum precipitation falling over periods of 3, 5 and 10 consecutive days (Finnis, 2013)	
Increase in the number of growing degree days (Finnis, 2019)	Increase in vegetation growth
Rise in sea level (Batterson and Liverman, 2010; James *et al.*, 2014)	Increase the height of extreme water levels, waves and high tide
Decrease in the duration and extent of sea ice (Savard *et al.*, 2016)	During the winter, an increase in the potential for large waves to form and for erosion from waves
Increase in severity and number of hurricanes over the Atlantic Ocean (Emanuel, 2005; Webster *et al.*, 2005; Mann and Emanuel, 2006) and in the severity of other storms (Forbes *et al.*, 2004)	Increase in movement of beach sediment and material from the base of cliffs, and in flood potential

2016). A gently sloping seafloor can lead to larger waves than a steep seafloor (Woodroffe, 2002). On narrow beaches, waves can reach the base of the cliff and remove sediment more frequently than on wider beaches; evidence of wave erosion includes the presence of a wave *notch* (Plate 5A) or an eroded scarp (Figure 2B).

The shoreline at Stephenville Crossing is predominately dissipative, whereas the shorelines at Port au Port, Kippens, Berry Head, Robinsons and St. David's are predominately reflective or intermediate between the two. The fetch in St. George's Bay is about 700 km, and the prevailing winds and waves approach from the west and southwest (Shaw and Forbes, 1992); the winter winds are especially strong (Government of Canada, 2016). As a result, during the winter, large, *destructive* waves remove sediment from the beaches and the base of cliffs. In the summer, *constructive* waves form, resulting in beach *accretion*, and erosion of the base of the cliffs is limited.

On the northern shore of St. George's Bay, beach width decreases from west to east; at Port au Port, the beach is 40 m wide, narrowing to about 20 m or less in the Kippens area, and waves only reach the cliff base during extreme events. On the southern shore of St. George's Bay, the beach is narrower (8 to15 m), and waves reach the cliff base frequently.

Beaches undergo cyclical short-term changes (*i.e.*, seasonal to annual), undergoing erosion and subsequent accretion but no long-term net changes. Sand-dune environments under normal conditions have sediment moved from the foredune (*e.g.*, storm waves, high-water events), to the nearshore, before being transported onshore to re-establish the dune system through wave and *aeolian* processes (Figure 2A, B). Dunes serve as sand reserves, from which wind transports the sand to the foredune or beach. In barrier beaches, waves breach barriers, move sediment and deposit it landward (Plate 4A).

Long-term decadal changes in beach morphologies are dependent on the rate of change of sediment load in and out of the system (*i.e.*, *sediment budget*), and sea-level fluctuation resulting in the landward or seaward migration (Figure 2C, D). If sediment loss exceeds sediment gain, the system has a negative sediment budget and the beach will move landward. Conversely, if sediment gain exceeds sediment loss, the system has a positive sediment budget and the beach moves seaward.

Longshore drift between Port au Port and Stephenville is from west to east, and on the southern shore is from southeast to northwest; the unconsolidated cliffs supply sediment and feed the barrier beach systems at Stephenville and Stephenville Crossing at the western end of the bay (Shaw and Forbes, 1992).

ANTHROPOGENIC FACTORS

Human activities have direct and indirect impacts, and modifications of the environment may unintentionally enhance erosion. Solid structures such as groins or jetties decrease longshore drift, resulting in the accumulation of sediment on the up-drift side, and erosion on the down-drift side of the structure (Plate 6A). Hardening of the coastline with boulders, concrete or other solid materials do cause beaches down-drift

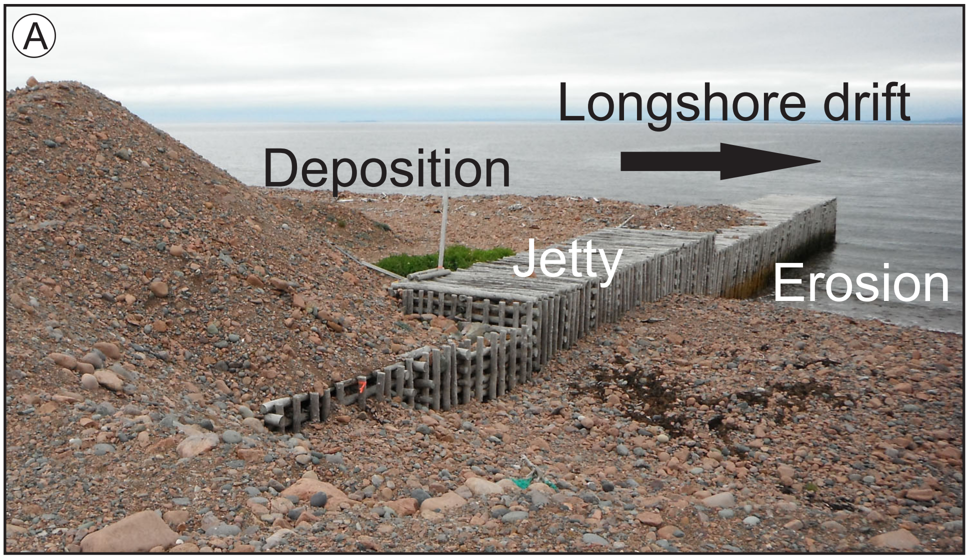


Plate 6. *Modifications to sediment dynamics in coastal environments. A) A jetty can cause disruption of sediment transport along the shore, resulting in the accumulation of sediment on the up-drift side of the structure, and erosion on the down-drift side. At Grand Beach, the jetty is limiting the amount of sediment entering the entrance to the community's harbour. The harbour entrance is to the right of the photograph; B) Large boulders were placed along the bank to prevent bank erosion in Conception Bay South. This modification impacts surrounding areas; by hardening the shoreline, sediment will no longer be supplied to beaches down-drift, leading to long-term erosion.*

to be starved of sediment (Plate 6B). The passage of all-terrain vehicles (ATV) and foot traffic on dunes cause erosion and enhance *blowouts* (Catto, 2002; Plate 7) and barrier beaches can also be artificially lowered by ATV use, resulting in an increased susceptibility to overwashing and breaching. Cliffs can be artificially advanced when material, such as grass or sediment, has been pushed or dumped over the edge; however, this seaward extension will likely only be temporary (Forbes *et al.*, 1995; Plate 8). The building of infrastructure on the top of a slope adds weight, which increases the *shear stress* on the slope; if the shear stress impacting a slope exceeds the shear strength, the slope will fail (Batterson and Stapleton, 2011). Housing, industrial and agricultural developments change the hydrological cycle, as the removal or modification of vegetation, irrigation, watering and paving of natural surfaces increases the quantity of surface and groundwater entering the coastal environment (Plate 2).

METHODS OF MEASUREMENT

The GSC conducted digital aerial *photogrammetry* of St. George's Bay, based on surveys flown in 1974 and 1986, to assess rates of coastal change for the 12-year interval, and an error of up to ± 2.2 m is attributed to their data (Forbes *et al.*, 1995). Field surveys were re-initiated by the GSC in 1991, repeated in 1993, 1994 and 2000, at five sites (Port au Port,

Plate 7. *The passage of ATVs and foot traffic impacts sand dunes by instigating wind erosion, which can result in blowouts. This example is from Lumsden, in northeastern Newfoundland (not in current study area).*

Plate 8. *Homeowners placed grass, woody debris and soil (circled) to advance the face of the cliff in Conception Bay South. As this material is loose, it is very vulnerable to erosion during a period of high wind or elevated water, and will likely be displaced during the next storm event.*

Romaines Brook, Seaside Drive, Marine Drive and Stephenville); data collected included ground measurements of shore-normal transects, extending from a benchmark on top of the cliff, down to the water, at various tide levels dictated by logistical considerations. The transects were surveyed using Real Time Kinematics (RTK) survey equipment (Table 3).

GROUND-BASED TOPOGRAPHIC SURVEYS

Between 2011–2014, the GSNL returned to the GSC monitoring sites and took new measurements. Additional new sites included Stephenville Crossing, Robinsons, Flat Bay, Berry Head and St. David's. Real Time Kinematic equipment collected precise (cm-scale) location data (Plate 9). The RTK equipment comprises a stationary base receiver (referred to as a 'base station'), one or more roving receivers, and a radio link. The base station is set up within 10 km of the monitoring site, over a permanent survey benchmark, and is in line-of-sight of the roving receivers. It continually collects satellite signals of its static location, and the positional errors (*e.g.*, satellite orbit errors) are transmitted to the roving receivers, allowing for the coordinates of the roving receivers to be corrected in real time, resulting in precise relative and absolute location data (Pardo-Pascual *et al.*, 2005).

Plate 9. *Real Time Kinematics survey equipment. The base station (yellow tripod) is set up over a previously established survey monument with known coordinates. The base station transmits reference position information to the roving receivers through the radio (blue tripod). The hand-held roving receiver, consisting of an antenna and field controller attached to a telescopic pole, is used during surveying.*

For accessible beaches and cliffs, between two and six shore-normal transects were surveyed, depending on the size of the monitored area (Plate 10A). For each shore-normal transect, a minimum of two survey markers, consisting of plastic pins attached to two-foot (0.61 m) pieces of rebar, were aligned perpendicular to the shoreline. The survey markers were installed landward of areas subject to active beach processes. Surveys were conducted from a landward survey marker to the edge of the water, along a transect line. For cliff sites, the clifftop and cliff base were surveyed with a measurement taken about every 50 cm. The clifftops are defined by a distinctive edge (Plate 10B) or, on vegetated slopes without distinctive edge, by a *break in slope* (Plate 10C). For dunes, transects and the foredune scarp were surveyed and measured approximately every 50 cm.

Table 3. Date, survey type and feature studied by the Geological Survey of Canada and the Geological Survey of Newfoundland and Labrador

Site	Year	Survey Type	Organization	Feature/Area
Port au Port	1993	Ground	GSC	Line 1
	1994	Ground	GSC	Line 1
	2011	Ground	GSNL	Lines 1-3, clifftop
	2012	Ground	GSNL	Lines 1-3, clifftop
	2013	Ground	GSNL	Lines 1-6, clifftop
Romaines Brook	1993	Ground	GSC	Line 1
	1994	Ground	GSC	Line 2
	2012	Ground	GSNL	Clifftop and base
	2013	Ground	GSNL	Clifftop and base
	2016	Aerial	GSNL	Entire area
Seaside Drive	1993	Ground	GSC	Line 1
	1994	Ground	GSC	Line 2
	2000	Ground	GSC	Line 2, Area A (Figure 8)
	2011	Ground	GSNL	Line 1, Area A (Figure 8)
	2012	Ground	GSNL	Line 2, Area A (Figure 8)
	2013	Ground	GSNL	Lines 2 & 3, Area A (Figure 8)
	2016	Aerial	GSNL	Entire area
Marine Drive	1994	Ground	GSC	Clifftop
	2012	Ground	GSNL	Clifftop
	2013	Ground	GSNL	Clifftop
	2014	Ground	GSNL	Clifftop
	2016	Aerial	GSNL	Entire area
Stephenville	1993	Ground	GSC	Lines 1-3
	2000	Ground	GSC	Lines 1-4
	2012	Ground	GSNL	Lines 1-4
	2013	Ground	GSNL	Lines 1-4
Stephenville Crossing	2013	Ground	GSNL	Lines 1-5, foredune
	2014	Ground	GSNL	Lines 1-5, foredune
Flat Bay	2011	Ground	GSNL	Lines 1-4, clifftop, cliff base
	2013	Ground	GSNL	Lines 1-4, clifftop, cliff base
Berry Head Cliff	2012	Ground	GSNL	Clifftop
Robinsons	2011	Ground	GSNL	Clifftop
	2013	Ground	GSNL	Clifftop
St. David's	2013	Ground	GSNL	Clifftop
	2014	Ground	GSNL	Area B (Figure 17)
	2016	Aerial	GSNL	Entire area

AERIAL SURVEYS

In 2016, a DJI Inspire 1 Quadcopter *unmanned aerial vehicle* (UAV) collected topographic data at sites previously surveyed using ground surveys (Plate 11). The Inspire 1 is equipped with a digital camera and controlled by an operator on the ground; while in flight, the camera takes overlapping aerial photographs. The UAV flights were planned in the Drones Made Easy Map Pilot web application. After takeoff, the UAV flew a pre-programmed itinerary at an altitude of 40 m, and images looking straight down at the ground taken automatically, with 80% overlap between each image (Figure 3). Subsequently the operator manually piloted the UAV, and instructed the camera to take overlapping photographs of the cliff face, using DJI Go, another web application. Ground-control points (GCP) were used to increase the horizontal and vertical accuracy (Hugenholtz *et al.*, 2016). Up to ten GCP were distributed throughout the surveyed areas before the flight, and their coordinates were measured using the RTK rover. The GCP consist of black and white targets, mounted on plywood, and are visible in the photos collected by the UAV (Figure 3).

After completion of the flight, the photos were loaded into AGISOFT Photoscan, a photogrammetry software that processed the 2-D images to produce 3-D objects using an algorithm that finds matching points on adjacent photos. The photos were aligned by matching the points on individual photos, and a sparse point cloud created. The accurately surveyed coordinates of the GCP were imported into Photoscan, and their location used to optimize the photo positions. Next, a dense point cloud was created. Based on the dense point cloud data, a polygonal mesh model and texture were constructed. Finally, a digital surface model (DSM) and orthophoto were created. The vertical and horizontal error of the surveys is ± 2 cm or less (Figure 3).

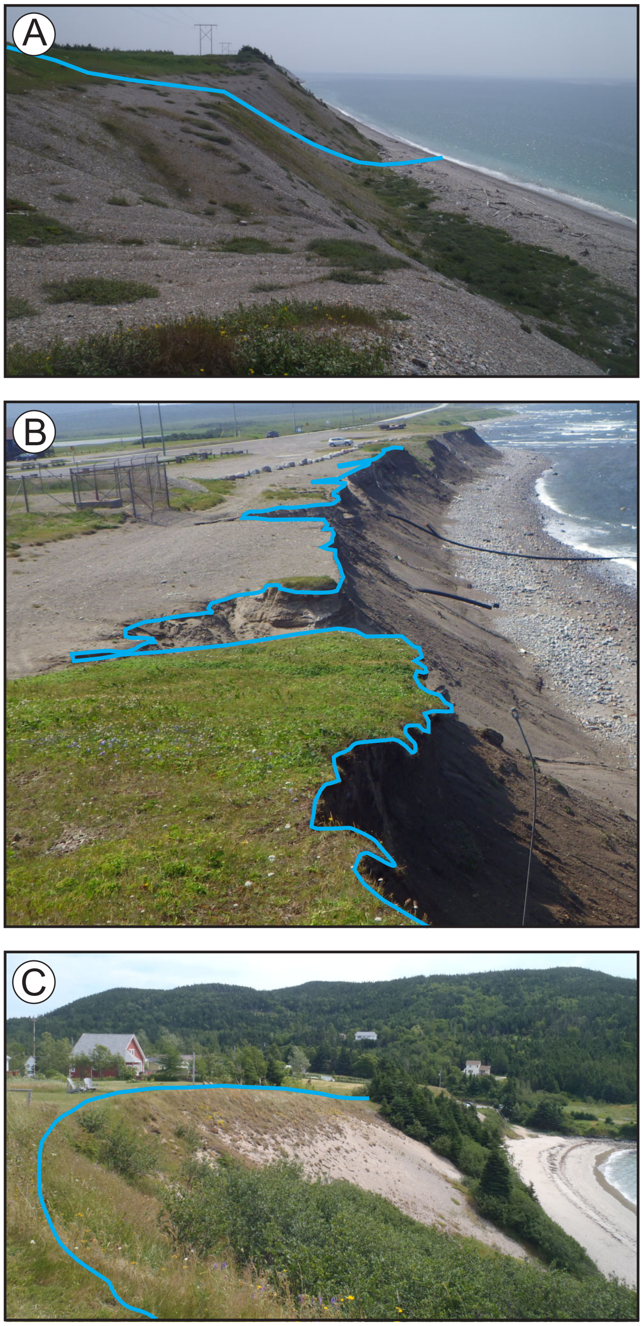


Plate 10. *Surveys can be conducted on shore-normal transects, clifftops or breaks in slope, indicated in blue. A) Shore-normal transect at Port au Port; B) Well-defined clifftop at Parsons Pond; C) Break in a vegetated slope at Sandy Cove.*

There are three main advantages of using the UAV, compared to the RTK system:

1) Access: Images of inaccessible areas, such as steep cliff faces or overhangs are accessed safely.
2) Quantity: The UAV collects data for the entire area, including the cliff face; the RTK only collects point data for the transect or feature being surveyed, typically the top and base of the cliff. Data are collected in a short time compared to the same area being surveyed with an RTK.
3) Quality: Data from the UAV is processed to create high-resolution imagery.

Plate 11. *The DJI Inspire 1 Quadcopter is a light UAV equipped with a digital camera, and is controlled by an operator on the ground using a hand-held controller.*

GROUND PHOTOGRAPHS

Older photos of coastal areas of St. George's Bay, prior to the 2000s, when compared to the present-day show significant changes in vegetation, sediment type, land use and geomorphology; however, rates of erosion, if any, cannot be determined.

QUANTIFYING EROSION RATES

Comparisons to quantify the rate of coastal erosion between ground and aerial surveys use the Digital Shoreline Analysis System (DSAS) software application for ArcGIS (Thieler *et al.*, 2009) to provide measurements of shoreline change following the steps below (Figure 4):

1) The point data collected by the RTK were imported into ArcMap, and using the point-to-line tool, a clifftop position for each year of data was created. For the aerial surveys, the position of the clifftop was digitized based on the *orthophoto* and the *digital surface model* (DSM).
2) A *baseline* was created landward of the clifftop positions.
3) The default parameters and settings in the DSAS toolbar were established as follows: the transect spacing was set

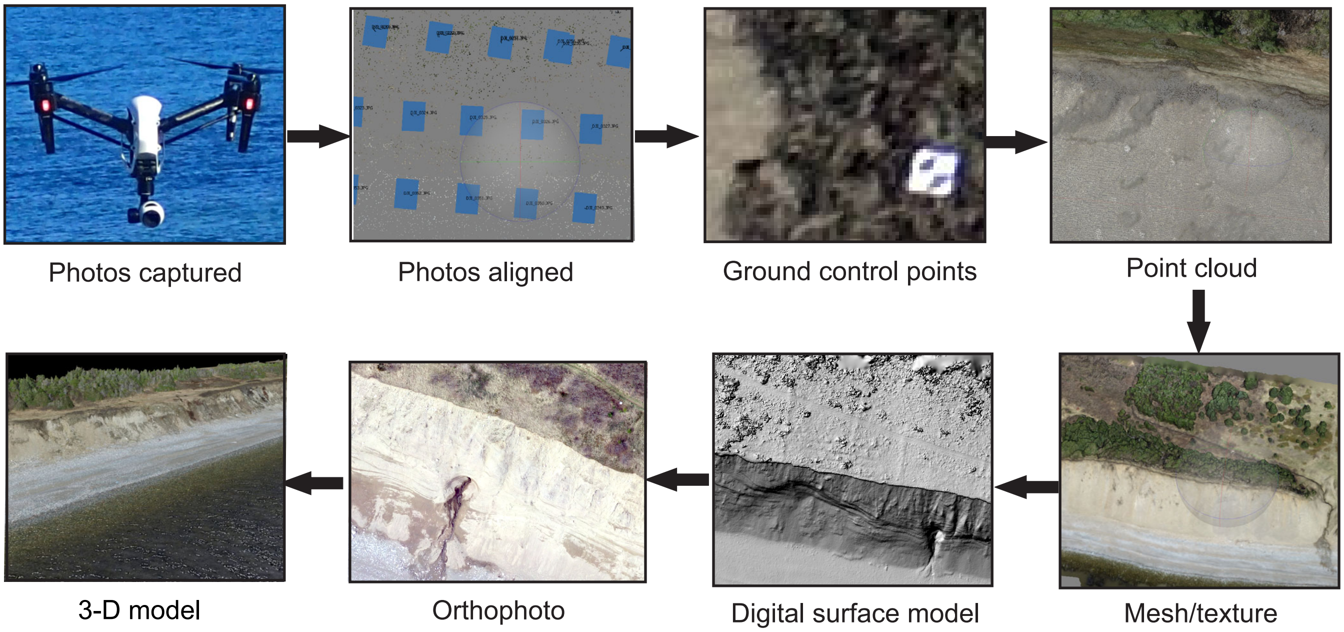


Figure 3. *Workflow for collecting and processing aerial data. Aerial images are collected by UAV, and downloaded into a photogrammetry program. Next, the photos are aligned, and ground-control data imported. A point cloud, mesh and texture of the field site are created. Finally, a DSM, orthophoto and 3-D model are constructed.*

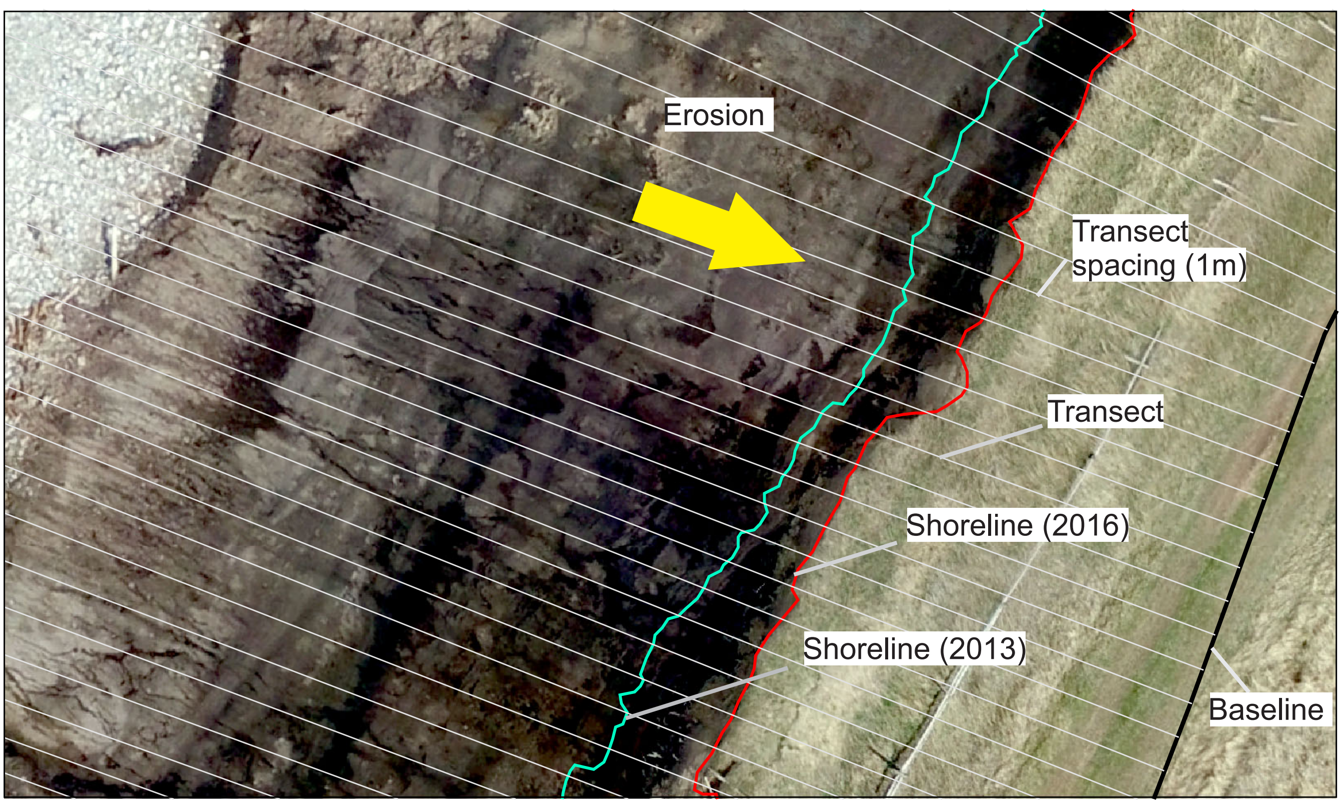


Figure 4. *The DSAS software application is used to calculate rates of erosion. The orthophoto is of the cliff at St. David's in 2016. The red line is the location of the edge of the clifftop in 2016, the turquoise line is the edge of the cliff in 2013, the black line is the baseline, the grey lines are the transects cast by the DSAS toolbar, and the yellow arrow indicates the direction of coastal erosion.*

to 1 m, the shoreline uncertainty set to 10 cm, and the appropriate baseline and shoreline layers selected.

4) Shore-normal transects spaced 1 m apart, extending from the baseline to the shorelines, were cast, and the transect layer created.
5) Rates of shoreline change were determined based on the intersection points of transects and shorelines. The DSAS provides different statistical options; this study used the End Point Rate (EPR) method. This is a common, simple and effective method to determine long-term shoreline change; it calculates the distance of total shoreline movement and divides this by the time interval between the first and last measurement.
6) End-point rates of erosion, as a function of distance along the shore, were overlain on the orthophoto. Colour and bar lengths represent the spatial variation in erosion at each site.

CHANGES IN BEACH PROFILES

To determine changes, vertical and horizontal changes in beach profiles are assessed. *Pythagoras' Theorem* is applied, using the easting and northing coordinates of an ordered pair of points to calculate the straight-line distance between them. Based on the results, profile graphs (plotting elevation change against distance) between the survey pin and the water are generated.

SOURCES OF ERROR AND DATA INACCURACY

Three main sources of error decrease data accuracy; these are:

- Instrument error. Instrument error for the RTK is related to errors in the satellite orbit, and *tropospheric* and *ionospheric delays*. Instruments are generally accurate to ± 1 cm in the vertical direction (elevation; Saghravani *et al.*, 2009), and less than 1 cm in the horizontal direction (easting and northing; Chekole, 2014). For the UVA, data accuracy is dependent on ground sample distance (GSD), which is the distance between two pixel centres measured on the ground. The lower the GSD, the higher the resolution of the image, and the more details visible. The GSD is determined by the sensor pixel size, focal length and the flight altitude (Torres-Sánchez, 2015). For the camera installed in the Inspire 1, the sensor pixel resolution is 12 megapixels and the focal length is 3.61 mm; the UAV was flown at an altitude of 40 m above the take-off location, resulting in a GSD of 2 cm (Maps Made Easy, 2017).
- Human error. The estimated human error of the survey data collected by RTK surveys is ± 10 cm. Inaccuracy is due to inadequately ensuring that the RTK rover pole is vertical in strong winds, and to uncertain definition and measurement of the cliff edge in areas where the latter is not well defined.
- Short-term noise. Using short-term data (less than 5 years) can result in the over- or underestimation of long-term rates of erosion; a minimum of five to ten years of data are required for reliable estimates of coastal change (Liverman *et al.*, 1994). A single storm can cause significant change to a beach or cliff; for instance, when estimating shoreline change between two observations, if a storm has strongly influenced the more recent shoreline position, the measured erosion will, if projected over a period longer than the period of measurement, result in the exaggeration of the actual long-term erosion (Dolan *et al.*, 1991).

The effect of these sources of error will decrease over time when the amount of coastal change exceeds the amount of error associated with the surveys, highlighting the importance of long-term data.

SITE SELECTION

Ten sites were monitored between the Port au Port Peninsula and St. David's (Figure 1). Site selection built on earlier studies by the GSC, to ensure representation of the diverse environments, and include locations that are undoubtedly undergoing erosion.

RESULTS

Factors affecting coastal erosion, for each site, are given in Table 4, and are detailed below. Rates of coastal erosion, and changes in beach profiles, are calculated for sites where more than five years of data have been acquired (Table 5; Port au Port, Romaines Brook, Seaside Drive, Marine Drive and Stephenville). Data for St. David's are also included because the rate of erosion has been rapid, and greater than the combined error in data-collection methods. Cliff-site environments are classified as either being stable (rate of erosion ≤ 9 cm/a), moderate (rate of erosion 10 to 29 cm/a), or rapid (rate of erosion ≥ 30 cm/a).

PORT AU PORT

The Port au Port sections and transects are on the *isthmus* leading to the Port au Port Peninsula, and cover cliff and beach environments (Figures 1 and 5; Plate 12). A 25-m-gravel- and sand-barrier beach encloses a *lagoon*; east of the lagoon is a sand and gravel, partly vegetated (*ca.* 30%) cliff, 30 m asl. The cliff-front beach is about 40 m wide and vegetated to the west; narrowing to 25 m and unvegetated, in the east. The site has a southwesterly exposure and a fetch of up to 500 km.

Table 4. Coastal characteristics of the monitoring sites

Site	Cliff Composition	Cliff Vegetation	Beach Composition	Evidence of Erosion: Wave	Ground-water	Surface water	Wind	Fetch: Distance (km)	Direction from
Port au Port	Sand, gravel	Partial (30%)	Sand, gravel	N	N	Y	Y	500	SW
Romaines Brook	Sand, gravel, silt, clay	None	Sand, gravel	N	Y	Y	Y	500	SW
Seaside Drive	Sand, gravel, silt, clay	Minor (5%)	Sand, gravel	N	Y	Y	Y	500	SW
Marine Drive	Sand, gravel	None	Sand, gravel	N	N	Y	Y	500	SW
Stephenville	N/A	N/A	Gravel	Y	N/A	N/A	N/A	500	SW
Stephenville Crossing	N/A	N/A	Sand	Y	N/A	N/A	Y	520	W, SW
Flat Bay	Gravel, sand, silt, clay	Partial (30%)	Sand, gravel	N	Y	Y	Y	520	W
Berry Head Cliff	Gravel, sand	Full	Pebbles, cobbles, boulders	N	N	N	N	500	W
Robinsons	Bedrock overlain by sand, gravel, silt, clay	None	Sand, gravel, boulders	N	N	Y	Y	460	W
St. David's North	Bedrock overlain by Sand, gravel, silt, clay	Minor (10%)	Sand, gravel, boulders	N	Y	Y	Y	460	W
St. David's South	Gravel, sand, silt, clay	None	Sand, gravel, boulders	Y	Y	Y	Y	460	W

Table 5. Rates of coastal erosion measured along the coast of St. George's Bay

Site	Location	Period	Feature	Erosion (cm/a): Cliff base	Clifftop	Geomorphic change
Port au Port	Line 1	1993-2013	Cliff transect	47	2	Minor erosion, steepening of cliff face
	Area A	1974-1986	Clifftop	N/A	5	Minor erosion
Romaines Brook	Line 1	1993-2013	Cliff transect	52	12	Moderate erosion, steepening of cliff face
	Line 2	1994-2013	Cliff transect	17	13	Moderate erosion, steepening of cliff face
	Area A	1974-1986	Clifftop	N/A	16	Moderate erosion
Seaside Drive	Line 1	1993-2011	Cliff transect	9	8	Minor erosion
	Line 2	1994-2016	Slope transect	N/A	N/A	Slumping
	Area A	1974-1986	Clifftop	N/A	16	Moderate erosion
	Area A	2000-2016	Clifftop	N/A	9	Minor erosion
Marine Drive	Area A	1994-2016	Clifftop	N/A	11	Moderate erosion
	Area A	1974-1986	Clifftop	N/A	11	Moderate erosion
Stephenville	Line 1	1993-2013	Beach transect	N/A	N/A	Accretion
	Line 2	1993-2013	Beach transect	N/A	N/A	Accretion
	Line 3	1993-2013	Beach transect	N/A	N/A	Accretion
	Line 4	1993-2013	Beach transect	N/A	N/A	Erosion
St. David's	Area A	2013-2016	Clifftop	N/A	21	Moderate erosion
	Area B	2013-2016	Clifftop	N/A	59	Rapid erosion

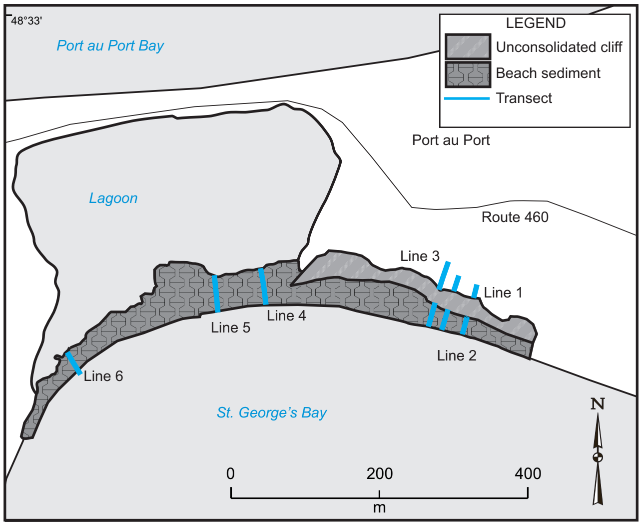


Figure 5. *Location of surveyed transect lines (blue lines) at the Port au Port site.*

Plate 12. *Partly vegetated gravel and sand cliff at Port au Port fronted by a gravel beach, July 2011. Erosion has been minimal along this coastline. Typically, waves do not reach the base of the cliff and groundwater is not present.*

Ground surveys were conducted by the GSC at the Port au Port site in 1993 and 1994, and between 2011 and 2013 by the GSNL (Figure 5; Table 3). Line 1 (GSC benchmark 264) shows clifftop erosion of 2 cm/a and cliff-base erosion of 47 cm/a, resulting in the steepening of the cliff face (Figure 6). The low rates of change of the clifftop (compared to other areas of St. George's Bay; *see* below), are consistent with the rate of coastal change measured at the same location for the interval between 1974 and 1986 (Table 5), which established a clifftop erosion rate of 5 cm/a (Forbes *et al.*, 1995).

Factors affecting cliff erosion:

- Loose sand is the dominant constituent making the cliff prone to erosion from wind and surface water.
- The site has a 500 km fetch to the southwest.

Factors inhibiting cliff erosion:

- The cliff face has approximately 30% grass and shrub coverage; the cliff is less susceptible to erosion from wind and water.
- The beach is wide (25 to 40 m); there is a well-defined beach *berm* on the beach face, and wave *notching* at the base of the cliff was not noted.
- There are boulders in the nearshore.

ROMAINES BROOK

The site is east of the mouth of Romaines Brook, and approximately 5 km west of Stephenville (Figure 1). The area is characterized by a 20-m-high cliff of glaciofluvial sand and gravel, underlain by silt and clay, and fronted by a 30-m-wide gravel and sand beach (Table 4; Plate 13).

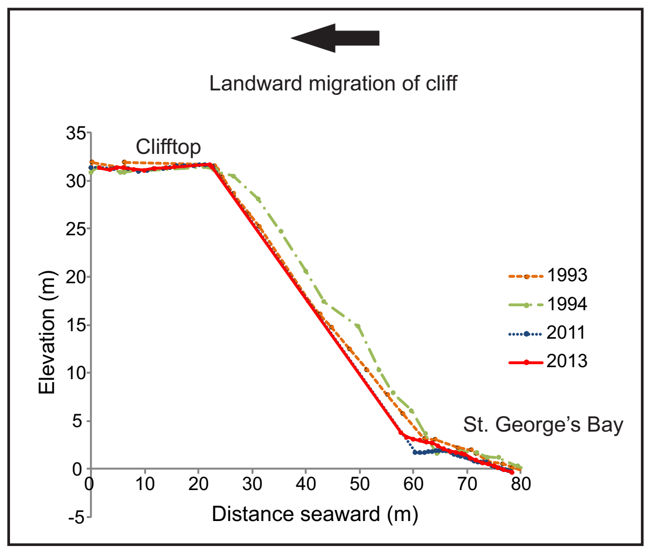
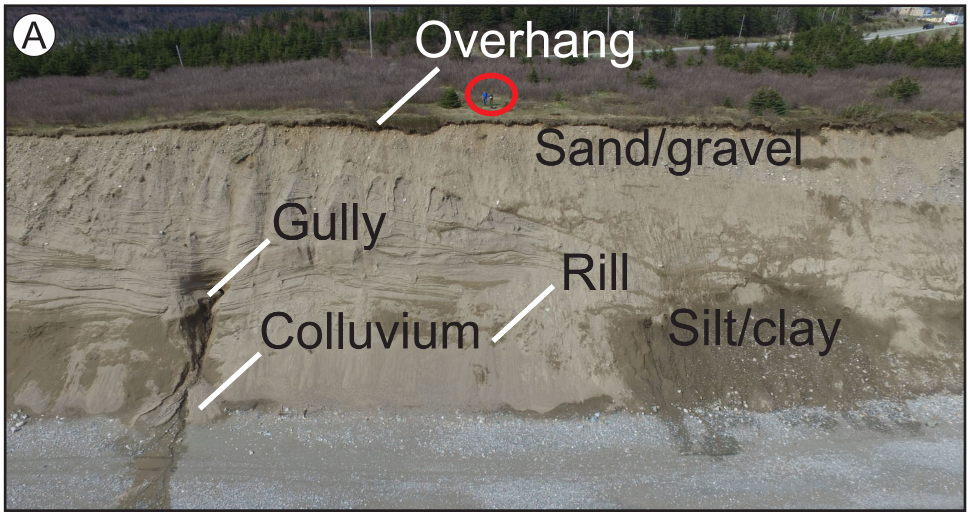
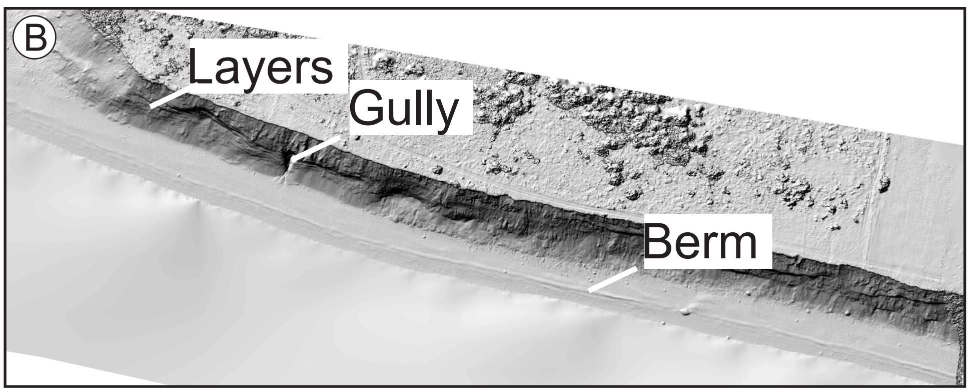


Figure 6. *Beach profiles between 1993 and 2013 for Port au Port, Line 3. The clifftop receded 16 cm (1.6 cm/a) and the cliff base receded 468 cm (46.8 cm/a) between 1993 and 2013. The cliff became more steep, and if this trend continues, the cliff will become increasingly unstable.*

Point measurements were taken by the GSC of the clifftop and base in 1993 and 1994, and GSNL surveyed the clifftop and base in 2012 and 2013. The clifftop has eroded at a rate of 12 cm/a between 1993 and 2013 at Line 1, and 13 cm/a between 1994 and 2013 at Line 2, respectively (Table 5; Figure 7). During the same period, at Line 1, the base of the cliff has eroded at a rate of 52 cm/a, compared to Line 2 where erosion has taken place at a slower rate of 17 cm/a. Forbes et al. (1995) documented the average rate of clifftop erosion between 1974 and 1986 to be 16 cm/a.





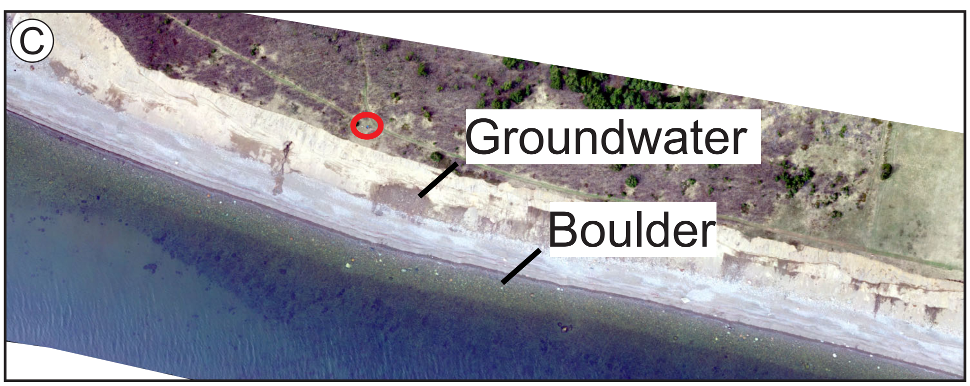


Plate 13. *Romaines Brook, Kippens, May 2016. A) View of the cliff face. The stratigraphy of the cliff varies, but consists mostly of silt and clay underlying sand and gravel. Groundwater is emerging from the contact between the sand and gravel layer, and that of silt and clay. Groundwater and surface water are resulting in gullying, rills and sheetwash, and sediment is being deposited at the base of the cliff. There are overhanging tuff mats along the top of the cliff. The surveyors are circled for scale; B) The hillshade of the DSM shows topographic features including the well-developed beach berm, cliff edge, sediment layers and gully. The left to right distance of the DSM is 370 m; C) The orthophoto shows boulders in the nearshore and groundwater exiting the cliff face. The surveyors are circled for scale. The left to right distance of the orthophoto is 370 m. The surveyors are circled for scale.*

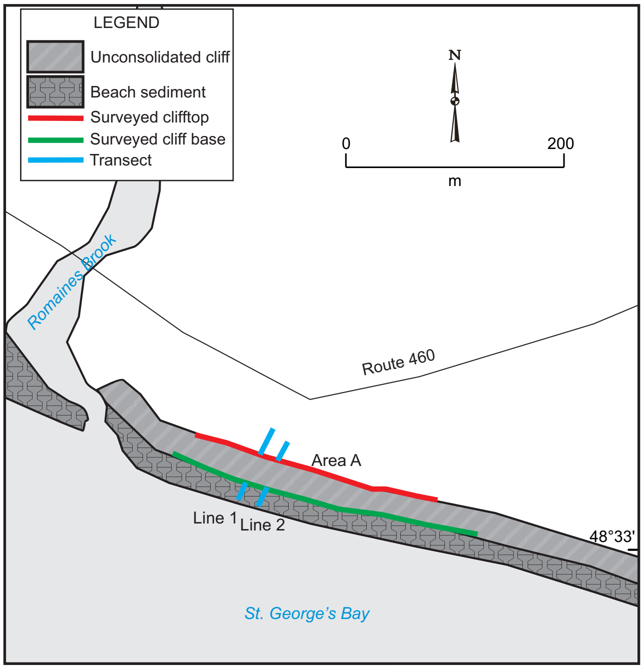


Figure 7. *Location of surveyed portion of the clifftop (red line), cliff base (green line) and transect lines (blue lines) at the Romaines Brook site.*

Factors affecting cliff erosion:

- The cliff is composed of silt and clay overlain by sand and gravel.
- Unvegetated cliff face.
- Gullies, rills, overhangs and colluvial material indicate that sediment is being removed from the cliff (Plate 13).
- The site has a 500 km fetch to the southwest.

Factors inhibiting cliff erosion:

- The beach is wide (over 30 m); there is a well-defined berm, and wave notching was not noted.
- There are boulders in the nearshore.

SEASIDE DRIVE, KIPPENS

This site is an unconsolidated sand, gravel, silt and clay cliff, up to 25 m asl and fronted by a beach 20 m wide (Figure 1, Plate 14). The cliff face is mostly unvegetated, exposed to the southwest, and has a fetch of up to 500 km (Table 4).

Ground surveys were conducted in 1993, 1994 and 2000 by the GSC and in 2011, 2012 and 2013 by the GSNL; the area was surveyed using a UAV in 2016 (Figure 8; Table 3). Between 1993 and 2011, at Line 1, the clifftop receded at a rate of 8 cm/a, and the base at a rate of 9 cm/a (Figure 9A; Table 5). In 2013, Line 3 replaced Line 1. At Line 2, there is no distinctive clifftop or cliff base, and between 1994 and 2016, the cliff face has eroded landward and material slumped downslope (Figure 9B).

The average erosion rate for Area A in Figure 8 between 2000 and 2016 is 9 cm/a (Figure 10; Table 5). Based on digital photogrammetry, between 1974 and 1986, the same receded at a faster rate of 16 cm/a (Table 5; Forbes *et al.*, 1995). It would appear that erosion is slowing, the cause of which is not clear.

Factors affecting cliff erosion:

- The cliff is composed of silt and clay, overlain by sand and gravel.
- Minor (5%) vegetation covers the cliff face.
- Gullies, rills, slumping, overhangs and colluvial material indicate that sediment is being removed from the cliff (Plate 14).
- The site has a 500 km fetch to the southwest.

Factors inhibiting cliff erosion:

- The beach is wide (25 m), there is a well-defined berm, and wave notching was not noted.
- There are boulders in the nearshore.

MARINE DRIVE, KIPPENS

The 19- to 25-m-high cliff at the Marine Drive site is unvegetated, composed of sand and gravel (Plate 15) and is exposed to the south and southwest; it has a fetch ranging between 220 and 500 km. A transect of 290 m of the cliff top was surveyed, at 40 cm intervals, in 1994, 2012, 2013, 2014 and 2016 (Table 3; Figures 1 and 11; Plate 15). Between 1994 and 2016, the clifftop erosion averages 11 cm/a (Figure 12), which is the same rate (11 cm/a) calculated from digital photogrammetry between 1974 and 1986 (Table 5; Forbes *et al.*, 1995).

Factors affecting cliff erosion:

- The cliff is composed of sand.
- Unvegetated cliff face.
- Rills, slumping, and overhangs indicate that sediment is being eroded from the cliff face (Plate 15).
- The site has a 500 km fetch to the southwest.

Factors inhibiting cliff erosion:

- The beach is wide (over 30 m); there is a well-defined berm, and wave notching was not noted.
- There are boulders in the nearshore.

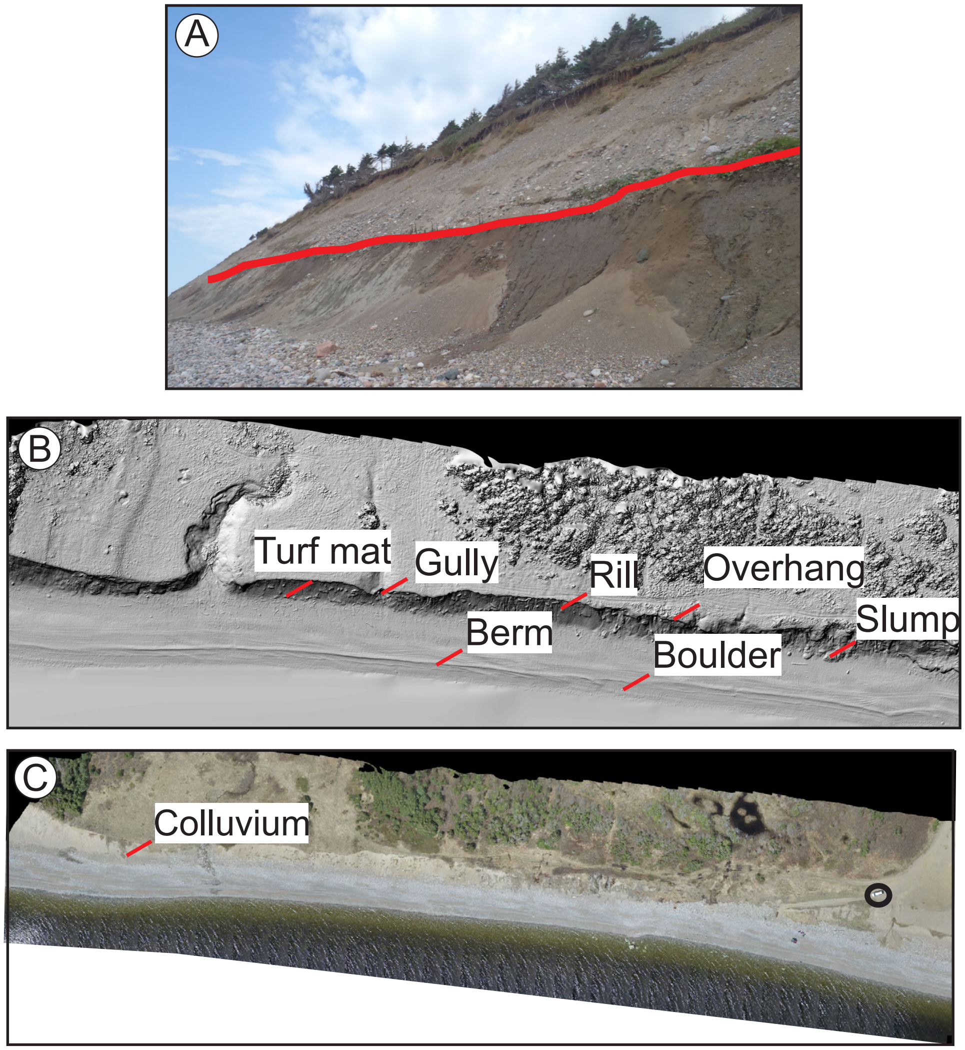


Plate 14. *Seaside Drive, Kippens, May 2016. A) View of the cliff face. Groundwater is coming out of the cliff face at the contact (shown by the red line) between the silt and clay layer and the overlying sand and gravel layer. The water is removing sediment from the cliff face, which is being deposited at the base of the cliff; B) A portion of the hillshade of the DSM, showing the beach berm, boulders, gullying, rills, slumped material, overhangs and turf mats. The left to right distance of the DSM is 330 m; C) Orthophoto of the western portion of the site. The central portion of the site has eroded at an accelerated rate. Note the truck circled for scale. The left to right distance of the orthophoto is 515 m.*

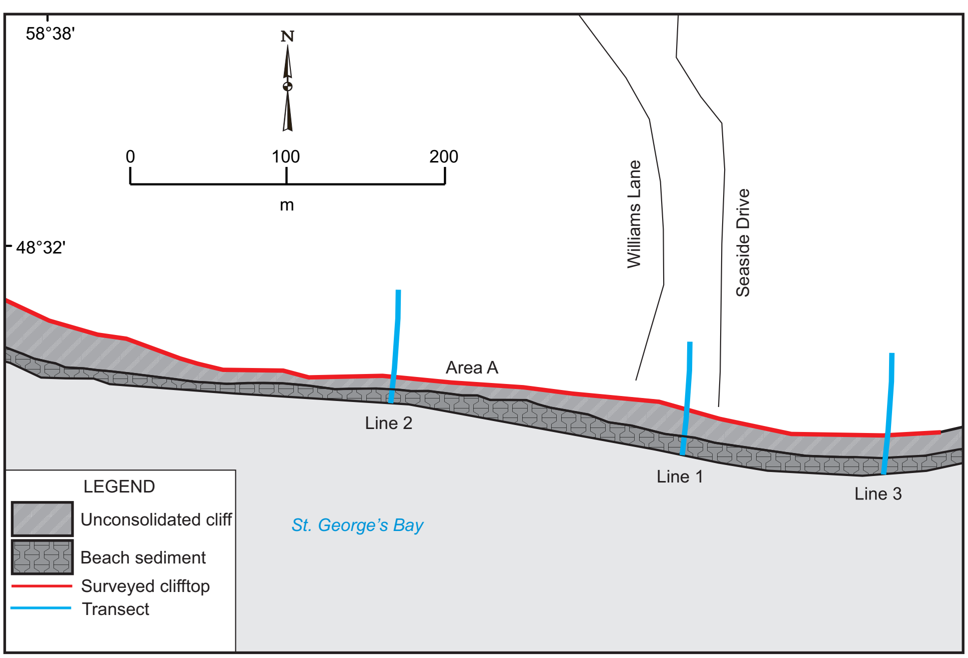


Figure 8. *Location of surveyed portion of the clifftop (red line), and transects (blue lines) at Seaside Drive, Kippens.*

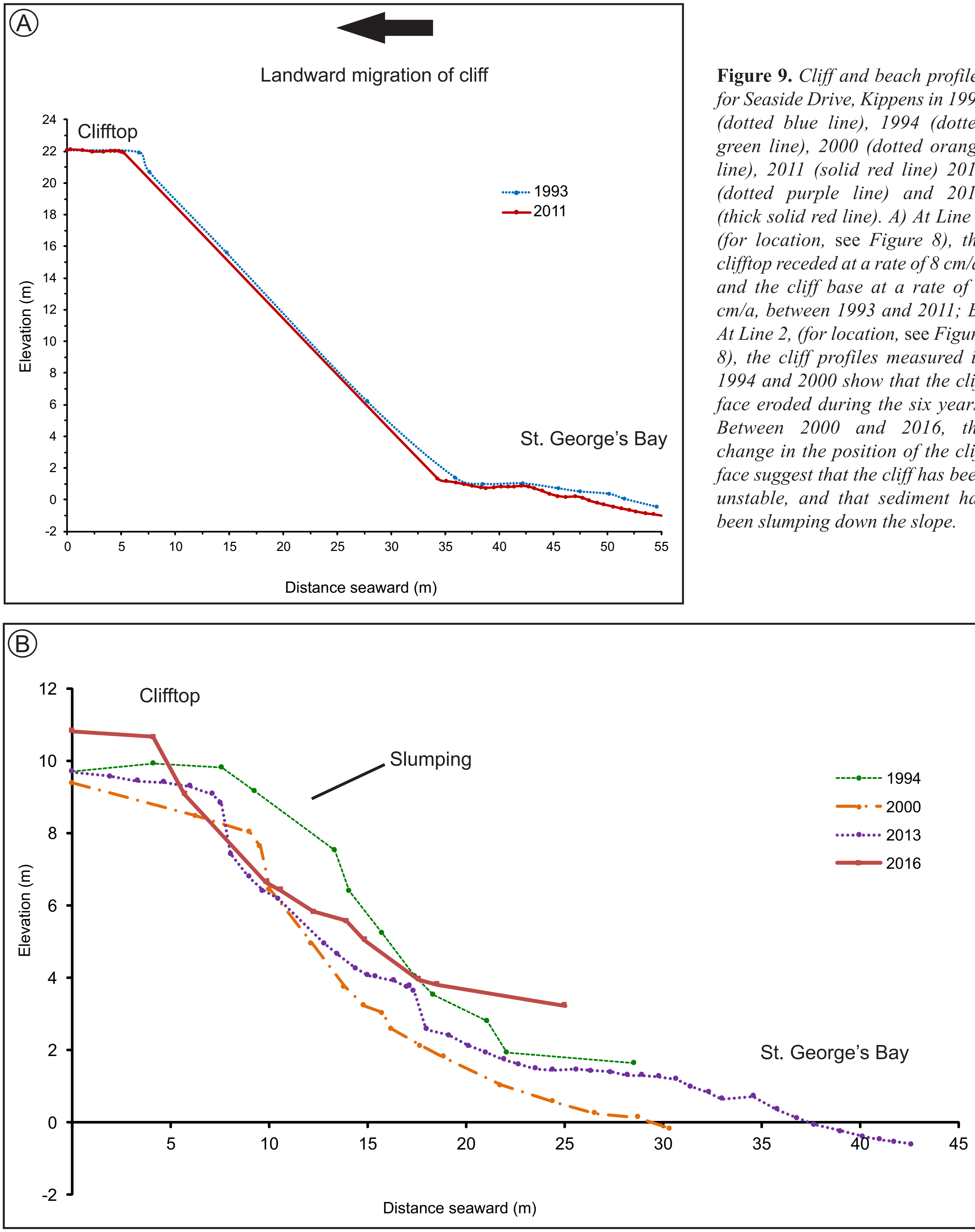


Figure 9. *Cliff and beach profiles for Seaside Drive, Kippens in 1993 (dotted blue line), 1994 (dotted green line), 2000 (dotted orange line), 2011 (solid red line) 2013 (dotted purple line) and 2016 (thick solid red line). A) At Line 1 (for location, see Figure 8), the clifftop receded at a rate of 8 cm/a, and the cliff base at a rate of 9 cm/a, between 1993 and 2011; B) At Line 2, (for location,* see *Figure 8), the cliff profiles measured in 1994 and 2000 show that the cliff face eroded during the six years. Between 2000 and 2016, the change in the position of the cliff face suggest that the cliff has been unstable, and that sediment has been slumping down the slope.*

Figure 10. *The DSAS analysis of coastal erosion from 2000 to 2016 along Seaside Drive, Kippens. Only the coastline west of Williams Lane (Figure 8) is displayed, to allow the coloured bars to be visible. Colour and bar length represent the spatial variation in erosion. The length of the bars represents the total amount (measured in cm) of clifftop erosion for the period of analysis; the longer the bar length, the greater the amount of coastal erosion. Red, yellow and green bars denote accelerated, moderate and minor erosion respectively.*

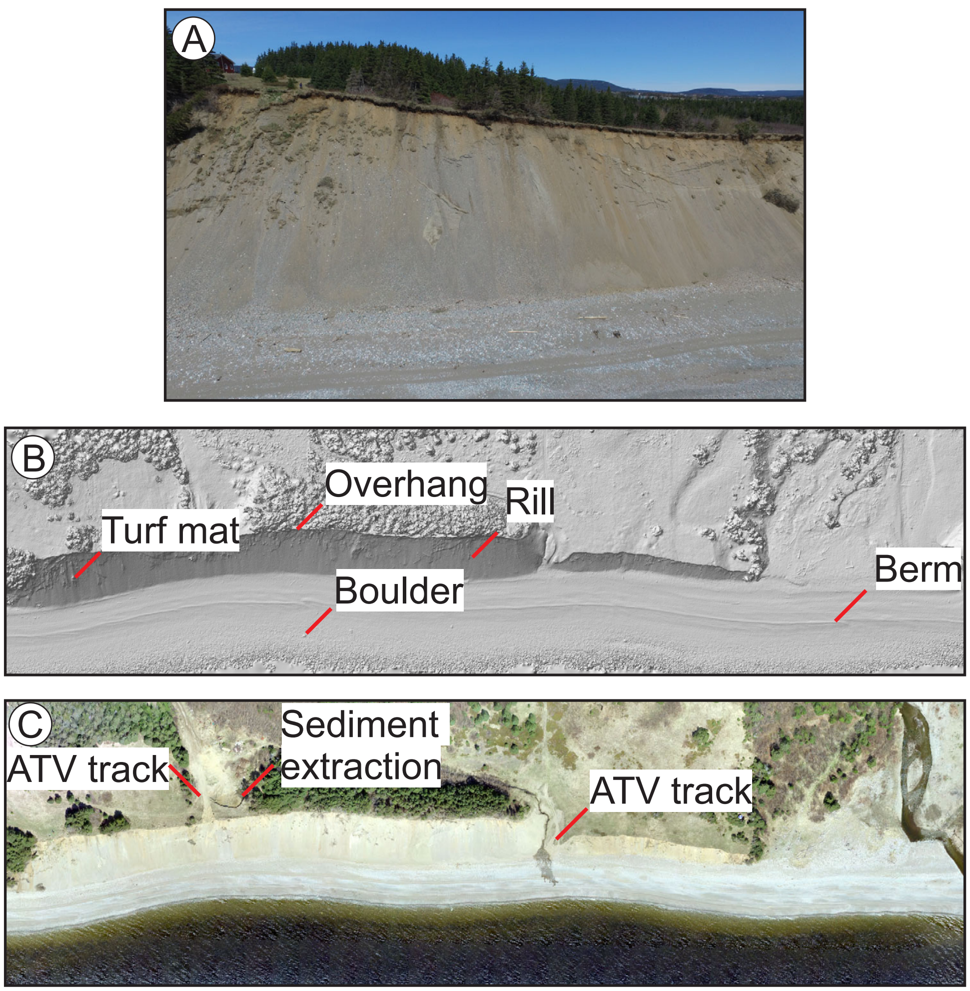


Plate 15. *Marine Drive, Kippens, May 2016. A) Sand and gravel cliff near Marine Drive, Kippens. Wind blows the sand from the cliff, and has created overhangs along the clifftop. Surface water is also resulting in cliff erosion; B) In the hillshade of the DSM a well-defined berm is visible, providing evidence that waves do not frequently reach the toe of the cliff. Boulders are visible in the nearshore, as well as turf mats on the cliff face and an overhang along the clifftop. The left to right distance of the DSM is 530 m; C) In the orthophoto, ATV tracks and the evidence of the exploitation of sand near the top of the cliff are visible. The left to right distance of the orthophoto is 530 m.*

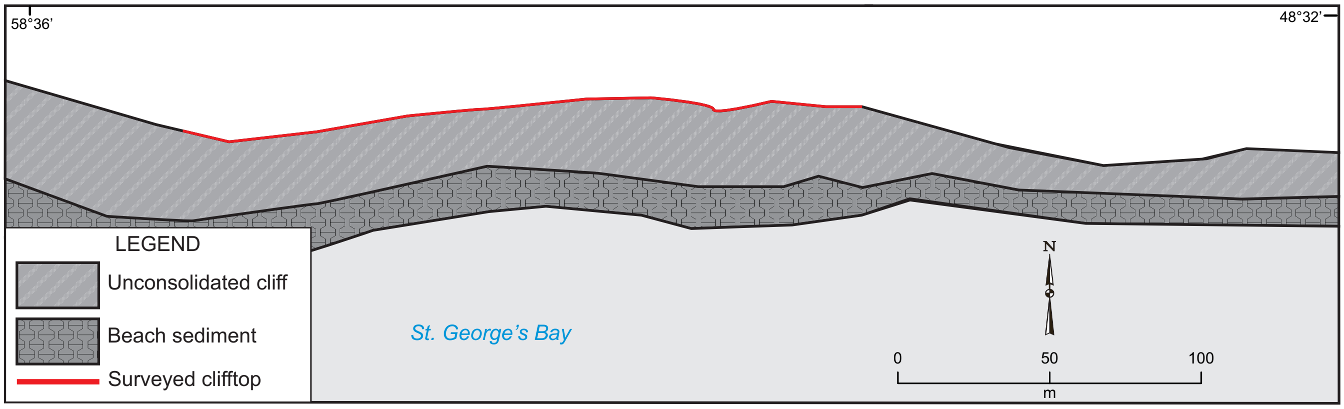


Figure 11. *Location of surveyed portion of the clifftop (red line) at Marine Drive, Kippens.*

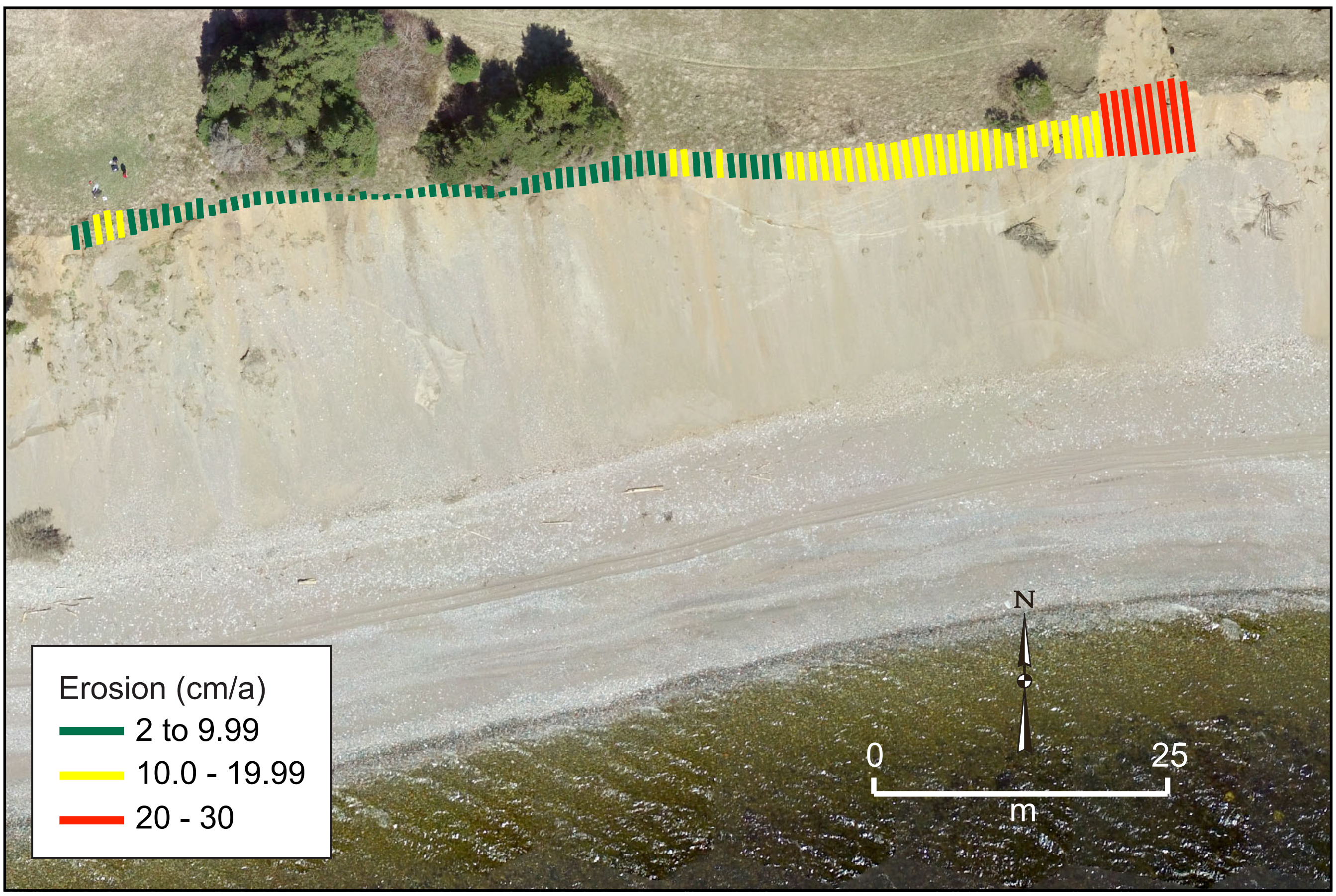


Figure 12. *The DSAS analysis of coastal erosion from 2000 to 2016 along Marine Drive. Colour and bar length represent the spatial variation in erosion. The length of the bars represents the total amount (measured in cm) of clifftop erosion for the period of analysis; the longer the bar length, the greater the amount of coastal erosion. Red, yellow and green bars denote accelerated, moderate and minor erosion respectively. Areas in red have been eroding at an accelerated rate, which was likely influenced by the passage of ATVs.*

STEPHENVILLE

The Stephenville site, on the northern shore of St. George's Bay, is about 5 km long (Figures 1 and 13). The site includes a barrier complex of Holocene beach ridges of well-rounded, flat gravel (Plate 16A). There is an artificial seawall parallel to the beach, and at the southern end, an artificial channel providing boat access to Port Harmon. Near Line 4, grasses overlie a sand *substrate* in the backshore (Plate 16B). Comparing a photograph from 1954 to field observations in 2012, it is evident that the sediment comprising the beach, in the vicinity of lines 1 to 3, has not changed significantly; in contrast, the beach in the vicinity of Line 4 has transitioned from a predominately sandy beach to one in which cobbles predominate (Plate 16). Four transects were surveyed between 1993 and 2013 (Figure 13); the volume of beach sediment has increased at Lines 1, 2 and 3, whereas at Line 4, the beach ridge has receded landward, as has the beach itself (Figure 14; Table 5).

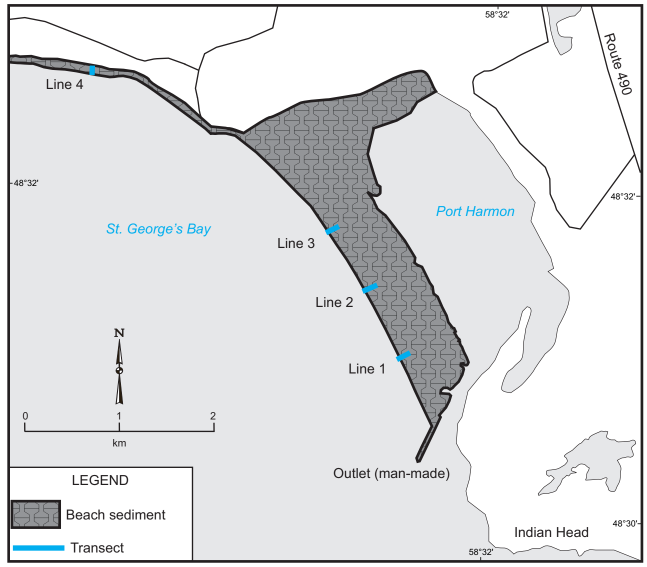


Figure 13. *Location of transects (blue lines) at Stephenville.*

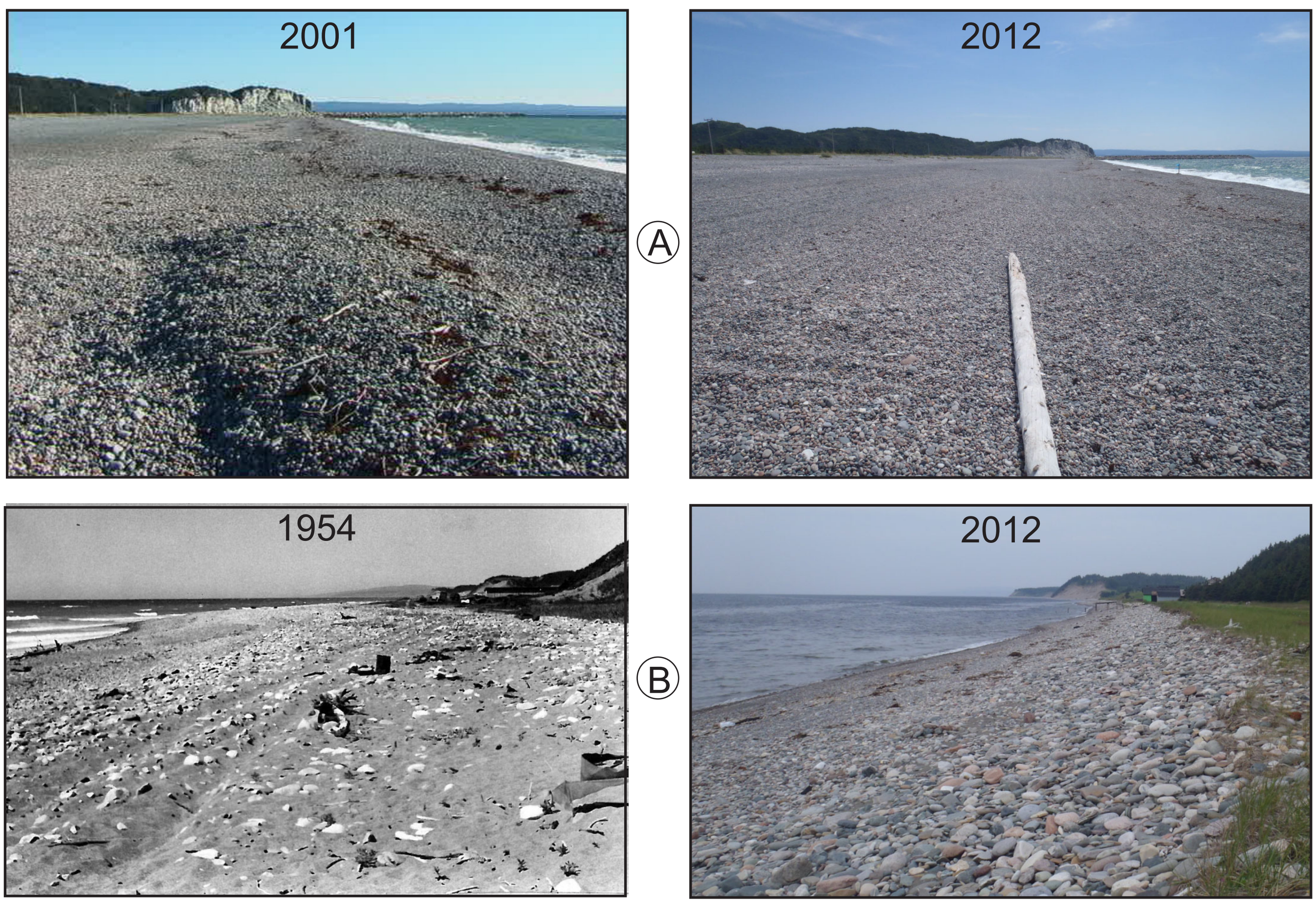


Plate 16. *Stephenville. A) Stephenville beach in 2001 (left) and 2012 (right) looking southeast, with Indian Head and the breakwater in the background. In the last 20 years, there has been accumulation of gravel on the beach face; B) Northern beach in 1954 (left) and 2012 (right). In 1954, there was more sand on the foreshore, whereas gravel is currently the dominant type of sediment.*

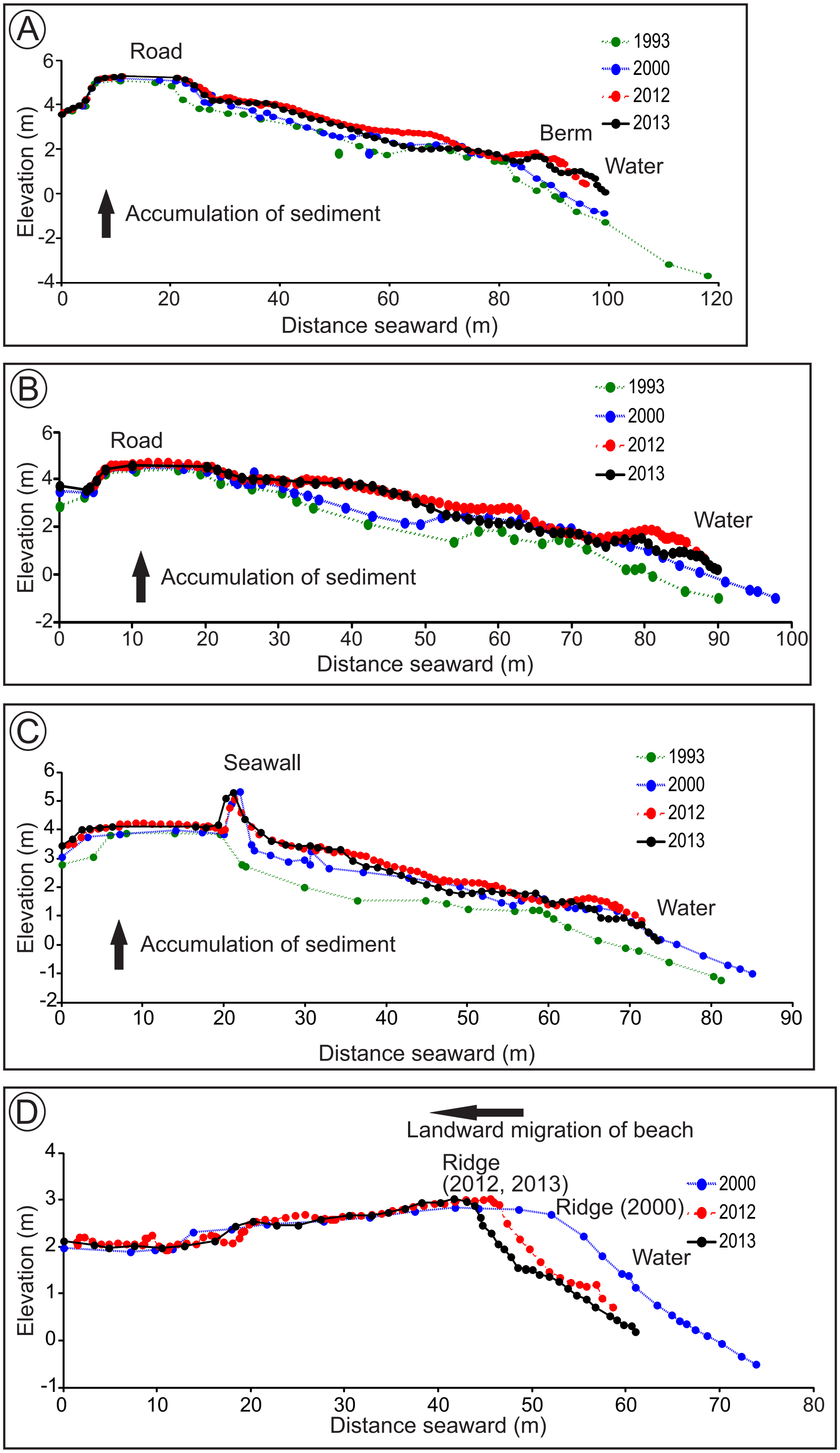


Figure 14. *Stephenville beach profiles from 1993 to 2013. See Figure 13 for the location of the transections lines. A) Line 1 shows a small increase in the volume of sediment over time, and variations in the location of the beach berms, with a vertical accretion in the lower foreshore in 2012 and 2013 compared to the previous years; B) On Line 2, the profiles show an increase in the beach volume between the earlier surveys (1993 and 2000) and the later survey years (2012 and 2013); C) Line 3 there has been an overall increase in the volume of sediment between 1993 and the more recent survey years (2000, 2012, and 2013); D) On Line 4, the beach ridge has been migrating landward and the beach face was steeper during the 2012 and 2013 surveys than in 2000.*

Factors affecting beach erosion:

- Longshore drift is from west to east; sediment eroding from the cliffs to the west is being deposited on the beach.
- The gravel on the beach is not susceptible to erosion from wind.
- The artificial channel is limiting the removal of sediment southeast of the beach.

Factors inhibiting beach erosion:

- The northern quarter of the beach has sand in the backshore and is only susceptible to erosion during high tidal events. The presence of driftwood and rounded beach cobbles landward of the ridge indicates that waves reach this area.

STEPHENVILLE CROSSING

The Stephenville Crossing site is a barrier dune complex at the head of St. George's Bay (Figures 1 and 15; Plate 17). It is exposed to the west and southwest and has a fetch between 250 and 520 km. Dunes vary in height from 1.6 to 4 m and sparse *embryonic dunes* are forming on the beach; blowouts up to 4 m wide have developed in the foredunes. Driftwood and seaweed were visible along the base of the dunes during site visits, indicating sediment accretion from waves. The mouth of the St. George's River forms a *tidal inlet*, Main Gut, through the southern end of the barrier, and longshore transport of sandy sediment from the west is feeding the barrier. Two areas of the seaward edge of the foredunes, and five transects, were surveyed in 2013 and 2014 (Figure 15; Table 3). Additional surveys are required to quantify rates of erosion. However, comparison of a photo of the beach north of St. George's River from 1954 to one from 2013 suggests that the sediment composition (gravel) and slope have remained the same overthe past 60 years (Plate 18).

Factors affecting beach erosion:

- Foot traffic has contributed to blowouts and initiated erosion.
- The site has a 520 km fetch from both the west and southwest.

Factors inhibiting beach erosion:

- Beach is wide (30 m); there is no scarp at the base of the dune. There are extensive dunes landward of the foredune (a potential supply of sand).
- The dunes are vegetated with grass and small shrubs, and sparse grass is present on the beach face.

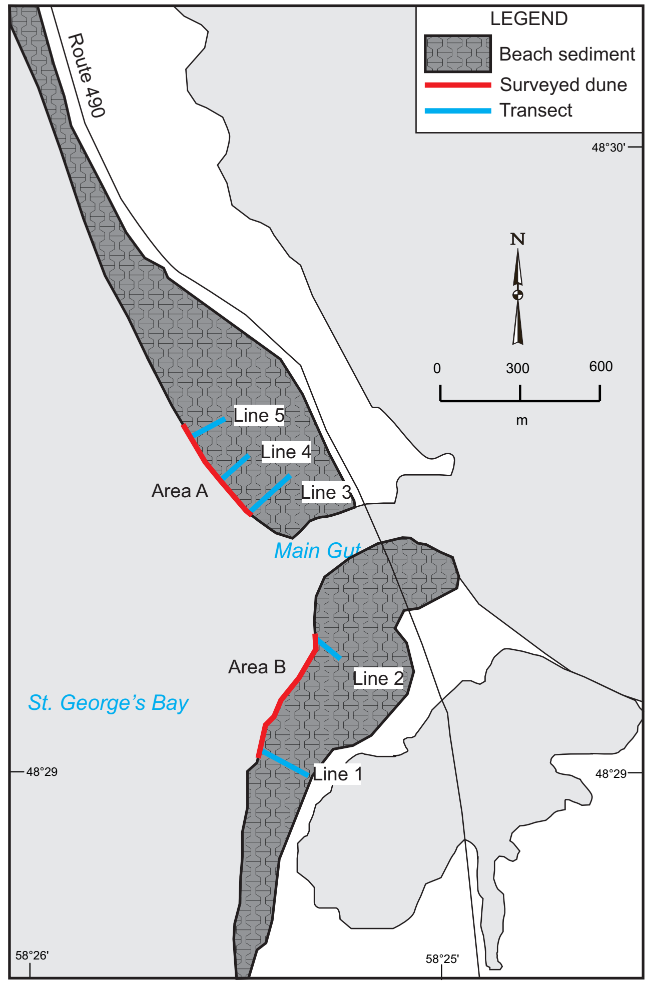


Figure 15. *Location of surveyed portion of the dunes (red lines) and transects (blue lines) at Stephenville Crossing.*

Plate 17. *Stephenville Crossing, June 2014. The dune field is well-vegetated, and embryo dunes have formed on the beach (example circled in red).*

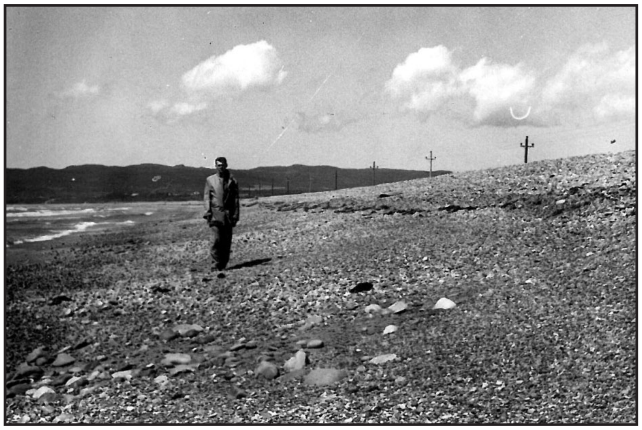


Plate 18. *The beach north of the Gut in Stephenville Crossing in 1954 (left) and 2013 (right). The beach has remained stable; the foreshore is dominated by gravel, backed by a steep ridge.*

FLAT BAY

Flat Bay consists of the Flat Island spit and the cliff to the southwest (Figures 1 and 16; Plate 19). The spit is 13 km long and about a kilometre wide, and consists of gravel and sand. The backshore is stable and vegetated with grass. The cliff southwest of the spit, whose top is 27 m high, is composed of gravel, sand, silt, and clay and is fronted by a low-gradient gravel and sand beach. The clifftop and cliff base and four shore-normal transects were surveyed in 2011 and 2013 (Table 3).

Factors affecting cliff erosion:

- The site has a 520 km fetch to the west.
- The cliff is composed primarily of sand and contains non-permeable silt and clay layers.
- Turf mats and colluvial material are signs that water has eroded cliff sediment.

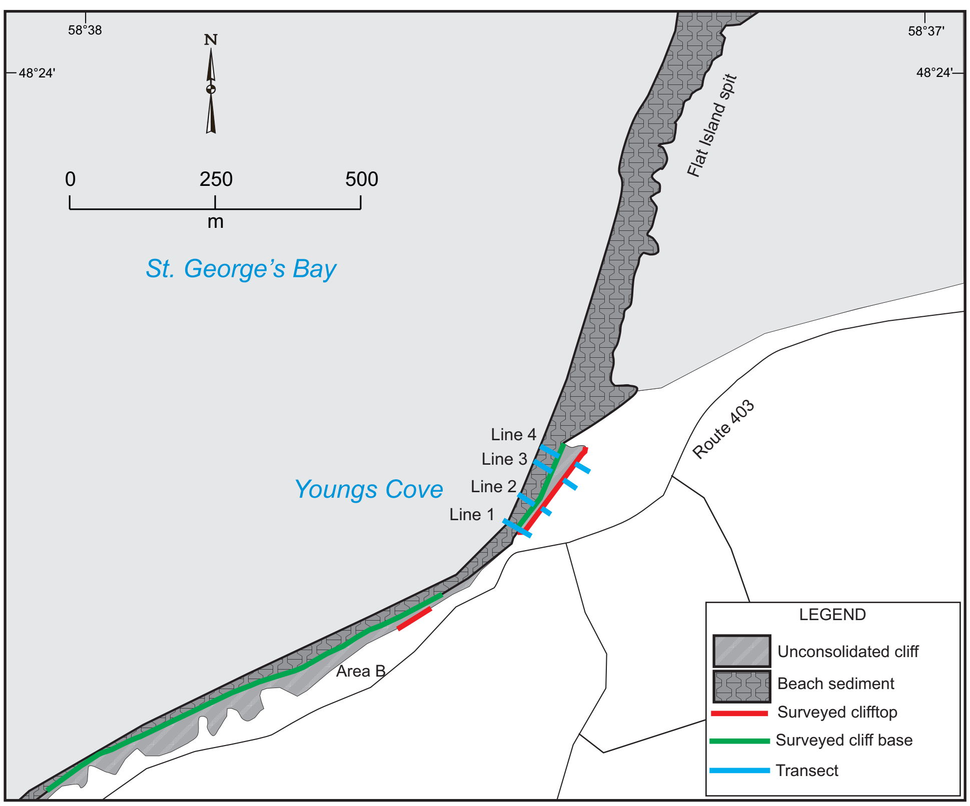


Figure 16. *Location of surveyed portion of the clifftop (red lines), cliff base (green lines) and transects (blue lines) at Flat Bay.*

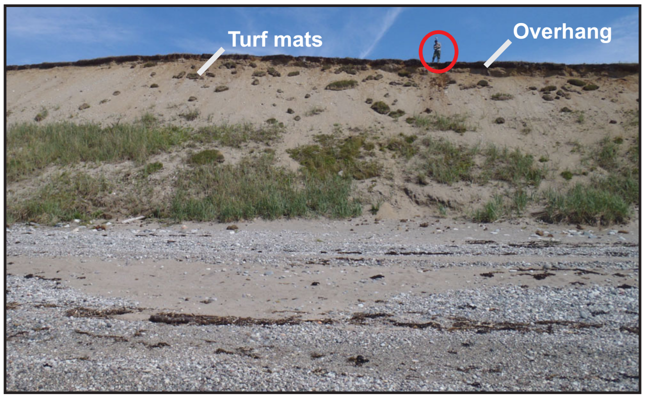


Plate 19. *The sand cliff near Flat Bay is being eroded, as evident from the turf mats on the cliff face, and the overhanging turf mat on the top of the cliff. Note the surveyor circled for scale.*

Factors inhibiting cliff erosion:

- The beach is wide (35 m), wave notching was not noted, and there is a seaweed line half-way between the cliff face and the high-water mark.
- The cliff face has about 30% grass and shrub coverage (more than most of the other locations studied in this report) reducing its susceptibility to erosion from wind and water.

BERRY HEAD

Berry Head, south of Flat Bay (Figure 1), is a vegetated cliff of gravel and sand, 30 m high (Plate 20; Table 4). The beach fronting the cliff consists of pebbles, cobbles and boulders. The surveyed area is exposed to the west and southwest,

Plate 20. *Vegetated cliff at Berry Head. As evident from the seaweed line along the beach face, waves typically do not reach the cliff base. The boulders (circled) near the waterline dissipate incoming wave energy.*

and has a fetch up to 500 km, due west. A 650 m transect of the clifftop was surveyed in 2012 and with measurements taken every 50 cm; field observations indicate the site is stable (Table 4).

Factors affecting cliff erosion:

- The site has a 500 km fetch to the west.

Factors inhibiting cliff erosion:

- The beach is wide, over 35 m; there is a well-defined berm, and wave notching was not noted.
- *Gullying* and slumping are not visible.
- There are boulders in the nearshore.
- The cliff face is entirely vegetated with grass and shrubs.

ROBINSONS

The monitored section, northeast of the Barachois River (Figure 1), is characterized by a coastal cliff 38 m asl. The cliff is composed of non-marine sedimentary rocks (Knight, 1983) overlain by sand, gravel, silt and clay (Table 4; Plate 21). The beach is narrow, comprising sand, gravel, and boulders. In 2011 and 2013, a 150 m segment of clifftop was surveyed with measurements taken every 30 cm using the RTK (Table 3).

Factors affecting cliff erosion here are:

- The site has a 460 km fetch to the west.

Plate 21. *Coastal cliff at Robinsons, June 2013. In contrast to the other monitored sites, the cliff is composed of sedimentary rocks overlain by sand and gravel. Although the sedimentary rocks are soft compared to many other types of bedrock, they are harder and more resistant to erosion than unconsolidated sediment. Wind and water can loosen and move rock fragments from the cliff face.*

- Cliff is unvegetated.
- Gullies and debris fans at the cliff base are signs that water has removed sediment.
- The beach is narrow (15 m).

Factors potentially inhibiting erosion:

- Boulders in the nearshore.
- The lower cliff is composed of friable sedimentary bedrock.

ST. DAVID'S

The St. David's survey site is on the north and south sides of Crabbes River (Figures 1 and 17; Table 4). The north side is a partly vegetated (*ca.* 10% cover), bedrock-dominated, non-marine *sandstone* cliff (Knight, 1983) overlain by sand, gravel, silt and clay between 5 and 10 m thick; the beach is narrow and consists of gravel, sand and rock (Plate 22). Along the south side, there is a 25-m-high unconsolidated cliff of interbedded medium to coarse sand and silt, and pockets of gravel that contain cobbles and boulders (Plate 23). The beach is narrow (about 15 m), and is composed of poorly sorted rounded boulders, gravel and sand.

In 2013, the north side of Crabbes River, a 150-m-clifftop transect was surveyed using the RTK; measurements were taken every 30 cm. Three years later in 2016, the same section was measured and photographed using a UAV (Table 3). The erosion rate for the clifftop has been 21 cm/a (Figure 18; Table 5).

Factors affecting cliff erosion:

- Gullies, rills, and *colluvium* at the cliff base indicate that sediment is being removed from the cliff face.
- About 10% of the cliff face is vegetated.
- The site has a fetch of 460 km to the west.
- Sand, gravel, silt and clay overly the bedrock.
- The beach is narrow (15 m).

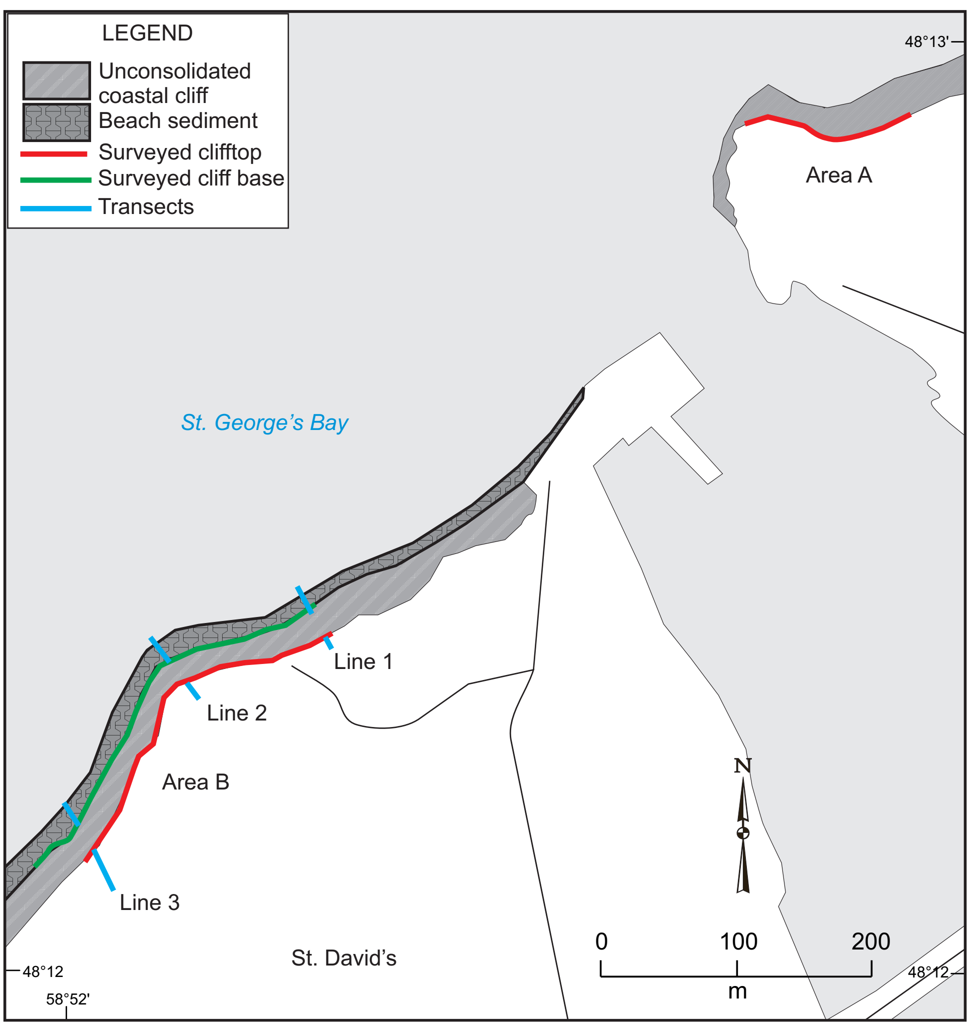


Figure 17. *Location of surveyed portion of the clifftop (red line), cliff base (green line) and transects (blue lines) near Crabbes River in St. David's.*

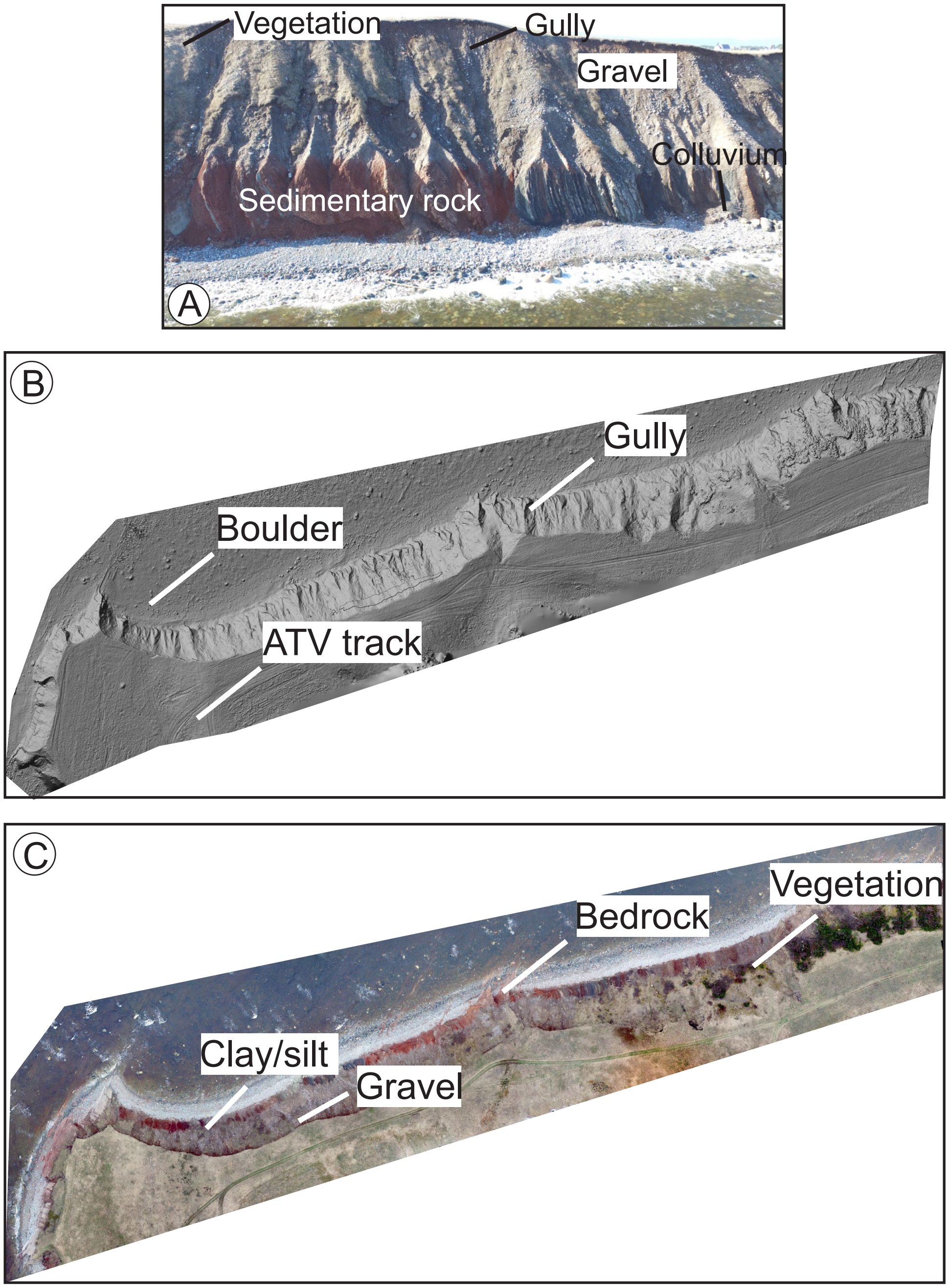


Plate 22. *Cliff north of Crabbes River, May 2016. A) Sedimentary rock, and overlying silt, clay and gravel, make up most of the cliff; B) Topographic features, including boulders in the nearshore, and gullies on the cliff face, are visible on the hillshade of the DSM. The left to right distance of the DSM is 630 m; C) The orthophoto shows the composition and vegetation cover of the cliff face; the dark red is bedrock, the smooth grey material is clay and silt, the white granular material is gravel, and the green is vegetation cover. The left to right distance of the orthophoto is 630 m.*

Factors potentially inhibiting cliff erosion:

- The lower cliff is composed of bedrock. Bedrock cliffs are generally more resistant to coastal erosion than unconsolidated cliffs.
- Boulders on the beach and in the nearshore.

In 2013, 2014 and 2016, the south side Crabbes River clifftop and base were surveyed (Table 3) and the average erosion for surveyed interval has been 59 cm/a (Table 5).

Factors affecting cliff erosion:

- Gullies, rills, overhangs and colluvium indicate that sediment is being removed from the cliff.
- Cliff is unvegetated.
- The site has a fetch of 460 km to the west.
- Sand, gravel, silt and clay comprise the cliff.
- The beach is narrow (15 m) and wave notching was noted.

Factors potentially inhibiting cliff erosion:

- Boulders on the beach and in the nearshore.

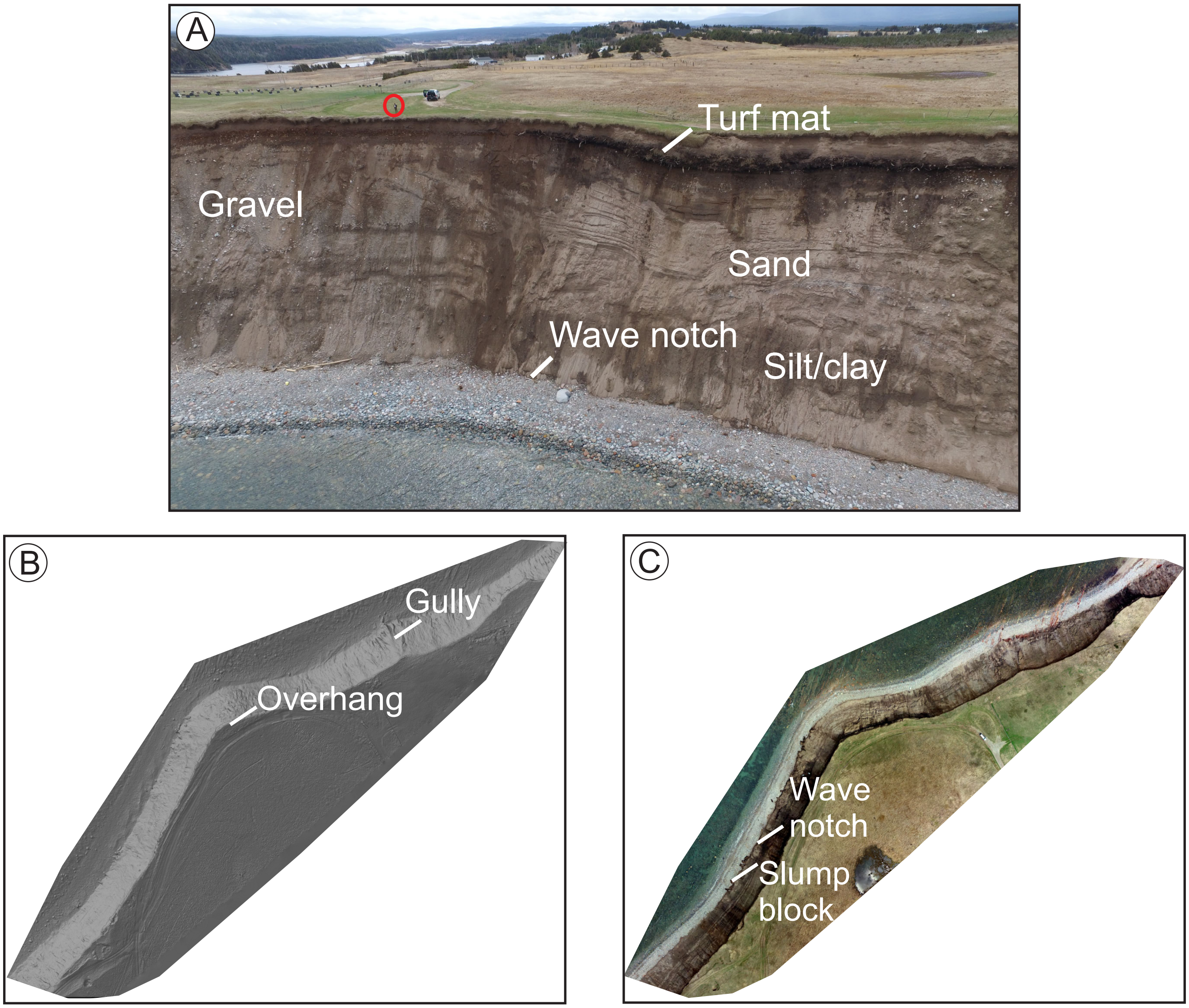


Plate 23. *Cliff south of Crabbes River, May 2016. A) The cliff is composed of sand and silt (darker sediment in photograph) with pockets of cobble and gravel. Along the top of the cliff is a layer of overhanging turf mats. Note surveyor circled for scale; B) The DSM shows gullies created by the passage of surface water and groundwater and overhangs created by wind. The left to right distance of the DSM is 500 m; C) The orthophoto shows slump blocks and wave notches at the cliff base. During high-water events, waves reach the base of the cliff and remove the loose sediment, resulting in erosion of the toe of the cliff. The left to right distance of the orthophoto is 500 m.*

SUMMARY OF COASTAL CHANGE AND IMPLICATIONS FOR PLANNING

At St. David's (South side Crabbes River average erosion 59 cm/a), where the narrow foreshore and large fetch allow waves to reach the cliff base, erosion is substantial when compared to elsewhere in the study area. On beaches, where waves do not reach the cliff, groundwater on unvegetated slopes appears to be the key factor influencing erosion. The average erosion for Romaines Brook has been 12–13 cm/a, 9 cm/a at Seaside Drive and 11 cm/a at Marine Drive. Port au Port is the most stable cliff area, with the average erosion rates of 2 cm/a; a wide beach and permeable (sand and gravel) cliff sediment result in waves and groundwater not contributing significantly to erosion.

Rates of coastal erosion will increase due to a changing climate (Table 6). For St. George's Bay, a major factor affecting rates of coastal erosion are sea-level rise and an increase in the intensity and frequency of storms. Along the northern

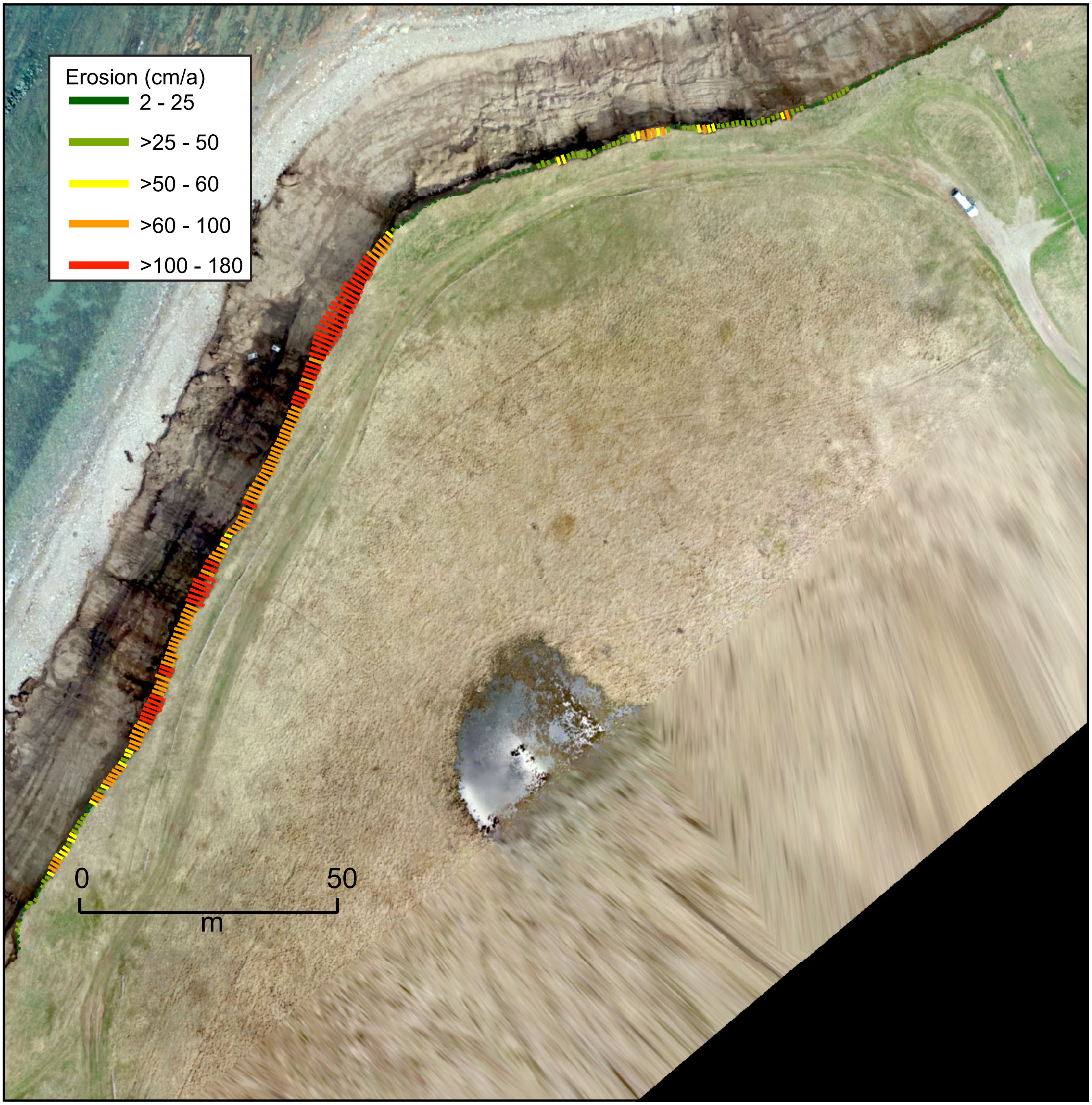


Figure 18. *The DSAS analysis of coastal erosion between 2013 and 2016 for the area south of Crabbes River in St. David's (Area B in Figure 17). Colour and bar length represent the spatial variation in erosion. The length of the bars represents the total amount (measured in cm) of clifftop erosion for the period of analysis; the longer the bar length, the greater the amount of coastal erosion. Red and orange bars denote accelerated erosion, yellow bars denote moderation erosion, and green bars decelerated erosion. There has been an acceleration of erosion south of the point where the aspect of the coastline changes from northward to northwestward.*

Table 6. Implications of climate change for coastal erosion

Consequence of Climate Change	Implication for Coastal Erosion
Increase in quantity of surface water and groundwater	Increase in clifftop and cliff face erosion
Increase in soil saturation	Increase in slope movement
Increase in vegetation growth	Increase in dune and slope stability
Increase in water levels	Increase in the extent and frequency of coastal flooding, increase in the erosion of the cliff base, and landward migration of beaches and dunes
In winter, increase in large waves reaching the coastline	Increase in the extent and frequency of coastal flooding, increase in the erosion of the cliff base, and landward migration of beaches and dunes
Increase in movement of beach sediment	Increase in the potential for new beaches to form, and for beach accumulation downdrift of areas of erosion

shore, and portions of the southern shore of St. George's Bay, waves do not reach the base of cliffs under normal conditions, and thus wave action does not contribute to significant erosion. When sea levels rise, rates of coastal erosion may increase substantially, and the cliffs currently experiencing moderate rates of erosion may experience accelerated rates.

Municipal planning and development in communities along St. George's Bay should consider rates of cliff erosion and coastal setback limits, which should aim for a 100-year planning time frame. To ensure that episodic events are accounted for, the suggested setback limit is twice the average yearly erosion rate, multiplied by 100. As a minimum of five to ten years of data are required for reliable estimates of coastal change (Liverman *et al.*, 1994) setback limits were calculated for sites with greater than 5 years of data, and are as follows:

- Port au Port: 4 m
- Romaines Brook: 24 m
- Seaside Drive, Kippens: 18 m
- Marine Drive, Kippens: 22 m

Within setback areas, changes to the physical landscape should be avoided, including modification of the vegetation and removal of sediment.

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APPENDIX A
GLOSSARY OF TERMS USED IN THE REPORT

The definitions in this glossary are taken mainly from *The Glossary of Geology* (Bates and Jackson, 1987), the *Dictionary of Geological Terms* (American Geological Institute, 1976) and *The Penguin Dictionary of Geography* (Moore, 1981). These definitions are specific to this study and to the science of coastal geomorphology; some terms may have different meanings in other contexts.

accretion The gradual or imperceptible increase or extension of land by natural forces over a long period of time, as on a beach by the washing up of *sand* or on a flood plain by the accumulation of sediment deposited by a stream.

aeolian Pertaining to the wind.

aggregate A mass or body of rock particles, mineral grains, or a mixture of both.

astronomical tide The hypothetical tidal level that would result from gravitational effects of the Earth, Sun and Moon, in the absence of ocean constraints and dynamics.

backshore The upper or inner, usually dry, zone of the shore or beach, lying between the high-water line of mean spring tides and the upper limit of shore-zone processes.

backwash The receding movement of sea water down a beach after the breaking of a wave.

barrier beach Depositional landform that is separated from the mainland coast by a *lagoon*, bay or marsh.

basal till A firm *clay*-rich *till* containing many abraded stones dragged along beneath a moving glacier and deposited upon *bedrock* or other glacial deposits.

baseline A line, normally straight, from which transects are set off, normally at right angles.

beach face The section of the beach normally exposed to the action of wave *swash*; the *foreshore* of the beach.

bedrock A general term for the rock that is usually solid, and underlies younger unconsolidated material.

berm A low, impermanent, nearly horizontal or landward-sloping bench, shelf, ledge or narrow terrace on the *backshore* of a beach, formed of material thrown up and deposited by storm waves.

blowout A general term for a small saucer-, cup- or trough-shaped hollow or depression formed by wind *erosion* on a pre-existing dune or other *sand* deposit.

break in slope A line along which the angle of a slope steepens noticeably.

clay A loose, earthy, extremely fine-grained, natural sediment or soft rock composed primarily of particles 0.001–0.004 millimetres in size, and characterized by high plasticity.

climate The average weather conditions of a place or region throughout the seasons (*cf.* weather)

coastal setback The distance from the coastline beyond which development is prohibited, restricted and/or discouraged.

colluvium Loose, weathered material brought to the foot of a cliff or some other slope by gravity.

constructive wave A wave that builds up a beach by moving material landward, as a gentle wave with a more powerful *swash* than *backwash*.

crest The highest point of a landform.

deglaciation The uncovering of a land area from beneath a glacier or ice sheet by the withdrawal of ice due to shrinkage by melting.

destructive wave A wave that erodes a beach by moving material seaward, as a storm wave with a more powerful *backwash* than *swash*.

detrital Pertaining to or formed from rock or mineral fragments.

digital surface model (DSM) A model that represents the solid surface of the Earth, including objects above it, such as trees and buildings.

dissipative beach A low, wide flat beach typically composed of *sand*.

dune field An area of moving and fixed *sand dunes*.

embryo dune A dune initiated seaward of the *stoss* slope of a *foredune*, where sand has accumulated within and behind individual plants on the backshore. On an accreting coast, the *embryo* dune will develop into a *foredune*.

erosion The general process or group of processes whereby the materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously moved from one place to another.

eustatic Pertaining to worldwide changes of sea level that affect all the oceans.

fetch The distance from a coastal area of open ocean, over which the wind blows with constant speed and direction, thereby creating a wave system.

fluvial Of or pertaining to a river or rivers.

foredune A coastal dune or dune *ridge* oriented parallel to the shoreline, more or less completely stabilized by vegetation.

foreshore The lower or outer, gradually seaward-sloping, zone of the shore or beach, lying between the *crest* of the most seaward *berm* on the *backshore* and the ordinary low-water mark.

geomorphic Relating to the form of the landscape and other natural features of the Earth's surface.

glaciofluvial Pertaining to the *meltwater* streams flowing from wasting (melting) glacier ice, and especially to the deposits and landforms produced by such streams.

glaciomarine Deposited by glacial meltwater in an ocean environment.

gravel An *unconsolidated*, natural accumulation of rounded rock fragments resulting from erosion, consisting predominantly of particles larger than *sand* (2 mm); or a popular term for a loose accumulation of rock fragments, composed predominantly of more or less rounded pebbles and small stones.

groundwater That part of the subsurface water that is in the zone of saturation, including underground streams.

gullies Distinct, narrow channels created by running water (*see gullying*).

gullying *Erosion* of soil or soft rock material by running water, forming distinct, narrow channels that usually carry water only during and immediately after heavy rains, or following the melting of ice and snow.

hillshade A relief map produced by simulating the appearance of sunlight and shadows, assuming an oblique light from the northwest so that slopes facing south and east are shaded, thereby giving a three-dimensional impression similar to that of a relief model.

Holocene An epoch of the *Quaternary period*, from the end of the Pleistocene, approximately 10 000 BP, to the present. The term "Anthropocene" is sometimes used to refer to the most recent part of the Holocene, after humans had evolved.

ionospheric delay The amount of additional transmission time a signal incurs as it passes through the ionosphere, 75–1000 km above the Earth.

isthmus A narrow strip or neck of land, bordered on both sides by water, connecting two larger land areas, such as a peninsula and the mainland or two continents.

isostatic change The vertical movement of the lithosphere (the rigid, outer part of the Earth) with respect to the asthenosphere (the mechanically weak region of the Earth's upper mantle).

lagoon A shallow stretch of seawater, such as a sound, channel, bay or saltwater lake, near or communicating with the sea and partly or completely separated from it by a low, narrow, elongate strip of land, such as a reef, barrier island, sandbank or *spit*.

longshore drift The transportation of sediment along a coast parallel or subparallel to the shoreline or the sediment moved by this process.

marine Pertaining to the sea.

marine limit The highest recorded level of late-glacial submergence, or former limit of the sea.

meltwater Water derived from the melting of snow or ice, especially stream water flowing in, under or from melting glacier ice.

notch A deep, narrow cut or hollow along the base of a sea cliff near the high-water mark.

notching Creation of a notch by undercutting due to wave *erosion*, and above which the cliff overhangs.

nearshore Extending seaward for an undefined but generally short distance from the shoreline. Specifically, extending from the low-water shoreline to beyond the breaker zone.

orthophoto A geometrically corrected aerial photograph or image.

overwash A mass of water representing the part of the *swash* that runs over the *berm* crest and does not flow directly back into the sea or lake.

permeable Having the property or capacity of a porous rock, sediment or soil for transmitting a fluid.

permanent water level network Network of permanent operational tide gauge stations that record water levels.

photogrammetry The art and science of obtaining reliable measurements from photographic images, especially air photographs, using computer hardware and software to facilitate the task.

Pleistocene Relating to or denoting the first epoch of the *Quaternary period*.

point cloud A set of points in the same coordinate system, representing the external surface of an object.

Pythagorean theorem The relationship between the lengths of the sides of a right-angled triangle: the sum of the squares of the lengths of the two shortest sides of a right-angled triangle is equal to the square of the length of the longest side. It is used for many applications, including finding the distance between two points.

Quaternary period The second period of the Cenozoic era, following the Tertiary. It began two to three million years ago and extends to the present.

ramp An inclined plane.

reflective beach A steep beach that is typically associated with coarser grained sediment.

relative sea level The height and position of the sea relative to the land. Relative sea-level changes are caused both by absolute changes of the sea level and by absolute upward and downward movements of the continental crust.

retrogressive landslide The retreat of a slide or flow in a direction opposite to the direction of the movement of material.

ridge A low, essentially continuous mound of beach or beach-and-dune material heaped up by the action of waves during high-water events and currently in the *backshore* of a beach, beyond the present reach of ordinary tides, and occurring singly or as one of a series of approximately parallel deposits.

rills Small channels created by concentrated water flow.

sand A rock fragment or *detrital* particle having a diameter in the range of 0.06 to 2 mm; or a loose *aggregate* of unlithified mineral or rock particles of sand size.

sandstone A porous *sedimentary rock* consisting of grains of *sand* bound together by such substances as calcium carbonate or silica.

scarp An almost vertical slope on a beach, caused by wave erosion. It may range in height from a few centimetres to a few metres, depending on the character of the wave action and the nature and composition of the beach.

sediment budget The balance of the sediment added to and removed from a system. A negative sediment budget occurs when more sediment is removed than is added, and a positive sediment budget occurs when more sediment is added than removed.

sedimentary rock A rock resulting from the consolidation of loose sediment that has accumulated in layers.

shear strength Resisting force acting on a slope.

shear stress Gravitational force acting on a slope.

sheetwash Unchannelled flow of water over a surface.

shore-normal At right angles to the shore.

shore water zone Land that is intermittently occupied by water as a result of the naturally fluctuating surface water level in a body of water, which can be either of fresh or salt water.

silt A rock fragment smaller than a very fine sand grain and larger than coarse *clay*, having a diameter in the range of 0.004 to 0.06 mm; or a loose *aggregate* of rock particles of *silt* size.

slope movement A term that includes all processes by which soil and rock material fail and are transported downslope by the direct action of gravity.

slumping The downward slipping of a mass of rock or *unconsolidated* material.

spit A small point or narrow embankment of land, commonly consisting of *sand* or *gravel* deposited by *longshore drift* and having one end attached to the mainland and the other terminating in open-water, usually the sea.

storm surge A change in sea level due to the result of wind stress and changes in atmospheric pressure.

substrate The substance, base or nutrient on which, or the medium in which, an organism lives and grows.

swash The advance of sea water up a beach after the breaking of a wave.

tidal inlet An inlet through which water flows alternately landward with the rising tide, and seaward with the falling tide.

tidal range The difference in height between consecutive high water and low water levels at a given location.

till Unsorted and unstratified sediment, deposited directly by a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of *clay*, *silt* and *gravel*, and boulders ranging widely in size and shape.

toe The lowest part of the slope or cliff.

transect A surveyed line along which measurements are made.

tropospheric delays The amount of additional transmission time a signal incurs as it passes through the troposphere, the layer of the atmosphere from the Earth's surface to 10 km above the Earth.

unconsolidated Loosely arranged or unstratified, with particles that are not cemented together as they would be in a rock.

unmanned aerial vehicle An pilotless aircraft operated by a remote controller or an onboard computer. A commonly used synonym is "drone".

vegetation line Edge of the zone within which vegetation is growing.

washover fan A fan-like deposit consisting of sand washed over a barrier during a storm.

weather Conditions of the atmosphere over a short period of time (*cf. climate*).

Wisconsinan Pertaining to the classical fourth glacial stage of the Pleistocene Epoch in North America.