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Barrier shoreline evolution constrained by shoreface sediment reservoir and substrate control: The Miquelon-Langlade Barrier, NW Atlantic

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ABSTRACT

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The Saint-Pierre-et-Miquelon Archipelago (France) is located in the NW Atlantic Ocean, proximal to the Cabot Straight outlet of the Gulf of Saint-Lawrence, and 50 km south of Newfoundland (Canada). The Miquelon-Langlade Barrier is a 12-km-long, 100-2500-m-wide, north-south–oriented isthmus connecting two bedrock islands (Miquelon to the north; Langlade to the south). This study aims to improve our understanding of shoreface-shoreline sediment exchange processes by comparing medium-term (1949-2011) shoreline changes, determined from aerial photographs and differential GPS data, with total shoreface sediment reservoir volumes estimated using seismic along the west coast of the Miquelon-Langlade Barrier. Spatial variability between the northern and southern sectors of the study site are seen both in the volumes of shoreface sedimentary reservoirs and in multi-decadal shifts of the shoreline position. The northern region has the lowest shoreface sediment volume and the highest rate of shoreline retrogradation. By contrast, the center and southern regions contain the largest volume of sediment in the shoreface and have demonstrated either long-term stability or progradation. This study demonstrates the primary roles of geological control and the distribution of shoreface sediments in local shoreline change at multi-decadal time scales. The sedimentary reservoir, in conjunction with shoreline-monitoring studies and knowledge of transport patterns, may provide a good alternative proxy.

ADDITIONAL INDEX WORDS: *Sedimentary shoreface reservoir, Shoreface/shoreline sediment exchange, Limited sediment supply, Bedrock influence, Saint-Lawrence Estuary, Mixed sand-and-gravel beach.*

INTRODUCTION

Barriers are depositional sedimentary features associated with a wide range of morphologies (e.g., barrier islands, barrier spits, welded barriers) that are found along coasts throughout the world (e.g., Davis and FitzGerald, 2004; Otvos, 2012; Stutz and Pilkey, 2011). Broadly speaking, barriers form via the accretion of sediment sourced from the shoreface or updrift deposits and transported landward or alongshore by waves, currents and aeolian processes. Barrier formation and long-term stability are influenced by sediment supply, bathymetry, tectonics, storms, anthropogenic activity and sea-level changes (e.g., Anthony and Blivi, 1999; Curray, 1964; FitzGerald and Heteren, 1999; Otvos, 2012; Riggs, Cleary and Snyder, 1995; Stutz and Pilkey, 2011). The processes responsible for the formation of coastal barriers have received a great deal of attention over the last 150 years (e.g., Stutz and Pilkey, 2011). Their fragility (low elevations, potential for remobilization of easily-erodible unconsolidated deposits, etc.), potential for anthropogenic modifications (tourism, economic development, etc.) and ecological importance underlie the importance of studying variability within these systems at short (annual- to decadal-) time scales. Generally, such studies have focused primarily on the processes and localized impacts of barrier overwash (Morton and Sallenger, 2003; Stone *et al.*, 2004), rather than the broader shoreline dynamics of barrier coasts.

Barrier systems can be divided into three morphologic zones: (1) the shoreface, defined as sub-tidal active zone with shallow-marine depositional system, (2) the barrier shoreline, consisting of the intertidal zone, beach-face, aeolian dunes, and washover deposits, and (3) the back-barrier, primarily composed of tidal flats, tidal creeks, marshes and/or lagoons. The study focuses on the interaction between the two first regions, i.e., the shoreface and the shoreline.

Shoreline dynamics can be understood through a variety of indicators (position of the high-water line, vegetation line, bluff top, etc.; Boak and Turner (2005)). Shoreline position is determined by the net balance between sediment accretion (generally resulting in regression, or a seaward translation of the shoreline) and erosion (generally resulting in transgression, or a landward translation of the shoreline). This behavior is controlled by hydrodynamic processes (waves, wind, tides and currents) that act on a number of temporal and spatial scales.

Similarly, the shoreface, and notably the upper shoreface (dominated by surf-zone processes), is impacted by the same

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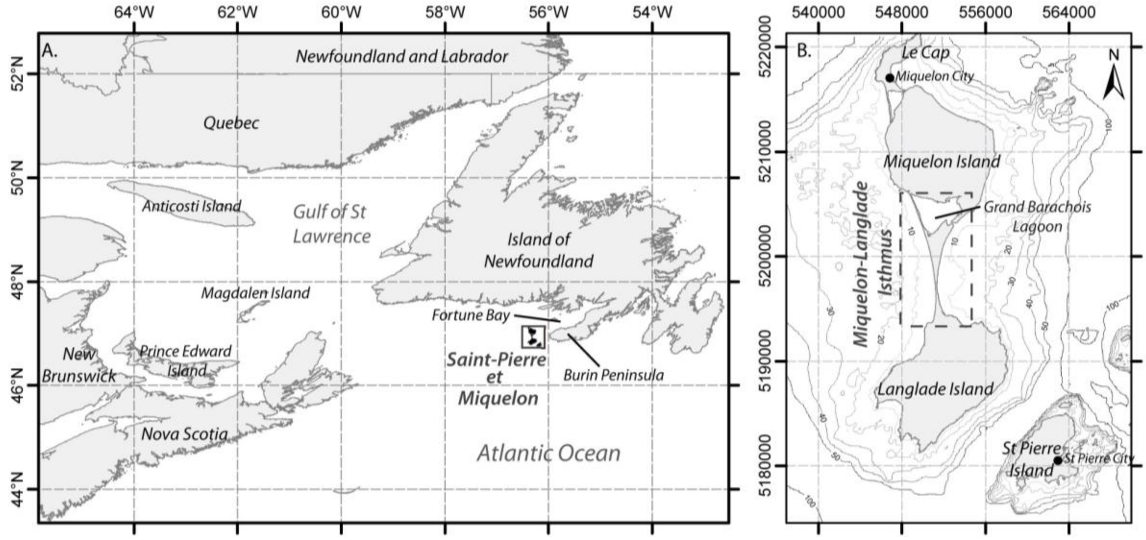

Figure 1. A) Location map of the Saint-Pierre-et-Miquelon Archipelago in the Gulf of Saint Lawrence (Canadian Atlantic). B) Detailed map of the Saint-Pierre-et-Miquelon Archipelago (planar projection UTM 21N). Bathymetric contours are in 10-m intervals.

processes that act along the shoreline. Here, these forcings drive complex sediment transport in both longshore and cross-shore directions (e.g., Anthony, 2008; Short, 1999). Thus, the availability of new sediment from the shoreface must also be accounted for in the consideration of the drivers of shoreline evolution, notably in sediment-starved systems. Potential shoreface sediment reservoirs (Certain *et al.*, 2005) and the rates and directions of sediment fluxes between the shoreface and shoreline are therefore important parameters to quantify. Unfortunately, due to the tendency to compartmentalize studies and focus on either the shoreface or the shoreline, such attempts at integrated understanding are rare.

This paper describes the erosional-depositional trends that occur along the west coast of the Miquelon-Langlade Barrier. The goal is to demonstrate the impacts on decadal shoreline evolution of sediment flux between the shoreface sediment reservoir and the adjacent shoreline. In this study, the offshore limit of the shoreface defined as the limit of the sediment cover (-17 m depth max.). Due to the sediment-starved nature of this coastline, the influence of shoreface geology is also investigated. The approach employs both modern shoreline monitoring (a 62-year record along 12 km of coast) and the calculation of the sand volumes on the shoreface. Comparisons are made only of shoreline evolution and bathymetric changes (Schwab *et al.*, 2000; Schwarzer *et al.*, 2003); shoreface morphodynamics are not considered. The Miquelon-Langlade Barrier is an excellent area to address these problems due to its relatively undisturbed setting: there is no history of offshore sediment extraction or dredging, the coast is fully undeveloped, and coastal structures are, with one exception, largely absent.

STUDY SITE

The Saint-Pierre-et-Miquelon Archipelago (France) is located in the northern Atlantic Ocean (Fig. 1.A), proximal to the Cabot Straight outlet of the Gulf of Saint-Lawrence, < 50 km south of Newfoundland (Canada). This archipelago is formed by three islands (Fig. 1.B): Saint-Pierre, Miquelon and Langlade. The latter two are connected by a mixed gravel-and-sand isthmus to form a single landmass. This barrier system is located along a bedrock-dominated shelf and is distal to any fluvial sediment sources. Sediment for construction of the isthmus was dominantly derived from local postglacial deposits (outwash sand cone and moraines) present throughout the archipelago.

This study is focused on the west coast of the Miquelon-Langlade Barrier, a 12-km-long, 50- to 2500-m-wide, north-south-oriented, Y-shaped isthmus (Figs. 1, 2). It is pinned at its northern and southern ends to subaerial bedrock. The northwestern section of the barrier is composed of a narrow (50-200 m wide) and high (up to 15-20 m) sand dune system, locally called "Les Buttereaux". The northeastern section of the barrier is composed of a sandy hooked spit, interrupted at its southern end by an active inlet that connects the sea to a 12 km^2 lagoon. The central and southern sections of the barrier are composed of well-developed, mixed sand-and-gravel beach ridge systems fronted by a modern foredune ridge. This section is lower in elevation, reaching only a few meters above mean sea level. The beach is composed of a mixed moderately-sorted sand (from south to north, mean grain size is between 0.16 and 0.50 mm) and gravel.

The beach slope is 6-16% and shoreface slope is 0.6-1%. During high wave energy events, wave swash can reach the dune foot. Tides along the Saint-Pierre-et-Miquelon Archipelago are semi-diurnal and microtidal, with a mean tidal range of 1.4 m at Saint-Pierre (Fig. 1). Mean annual waves have a height of 1.8 m and a period of 8.3 sec, as recorded at a buoy 6.1 km south of Saint-Pierre Island. The wave regime is dominated by regular, high-energy Atlantic swells from the west to south, with significant wave heights of 4-5 m and a maximum height of 8.4 m. Thus, the western shore of the barrier receives the dominant wave energy, whereas the eastern shore is largely protected by nearby Newfoundland, which limits fetch and wave energy. Winds are chiefly from the southwest to northwest with a mean annual velocity of 6.5 m/s (© Météo France database from 1998 to 2012). Storms, often in the form of subtropical depressions or the tailing edges of tropical cyclones, are frequent, and can induce wind gusts of up to 100-150 km/hr. Longshore transport along the high-energy west coast occurs in opposite directions: to the south in the northern section and to the north in the southern section (Robin, 2007). Longshore transport converges in the narrowest section, where the barrier is only 200 m wide.

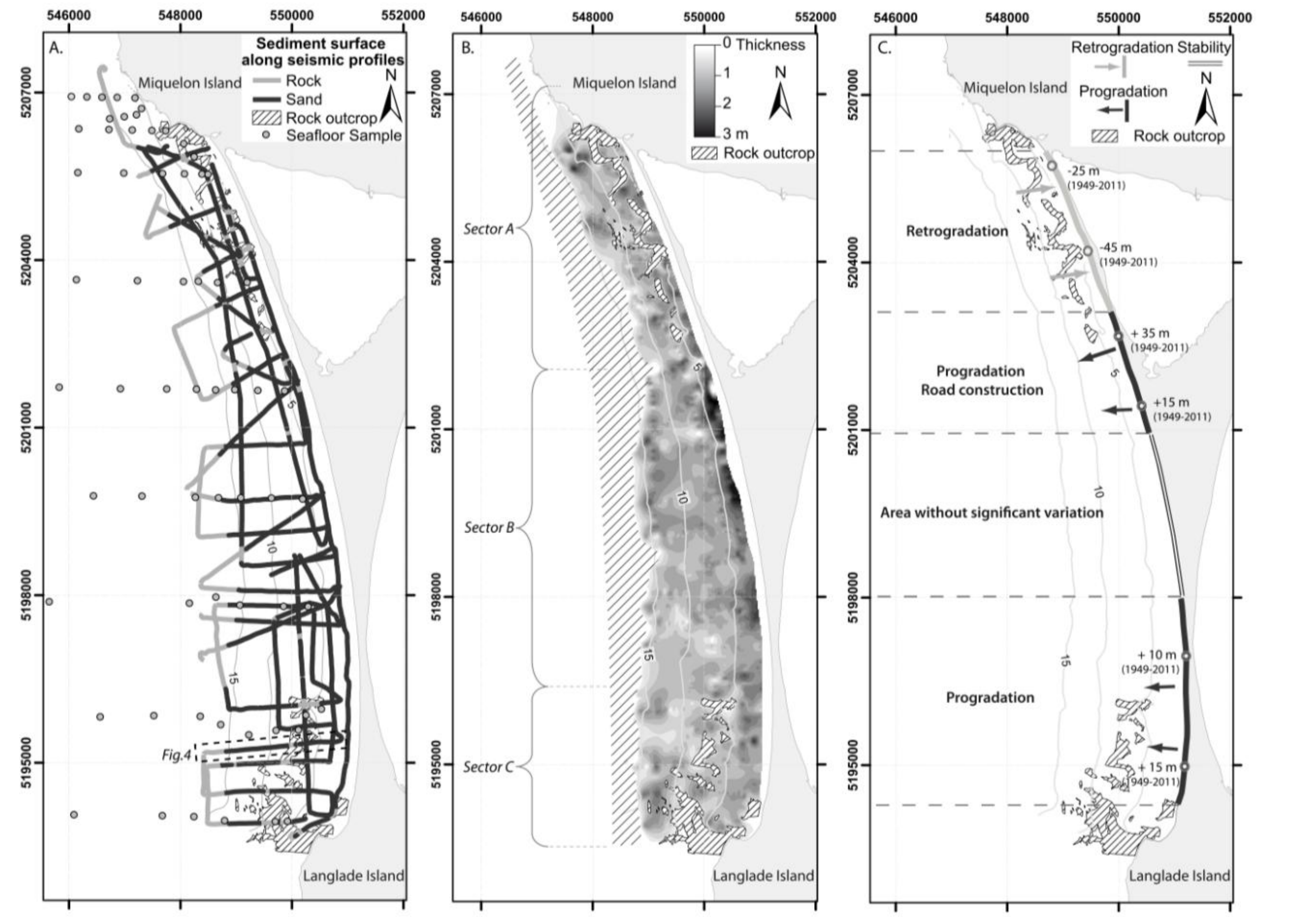

Figure 2. A) Location map of seismic profiles along the west coast of the Miquelon-Langlade Barrier. Black (sand) and gray (rock) lines correspond to the lithology of the seafloor along each profile. B) Isopach map of sand thickness, in meters. C) Shoreline evolution between 1949 and 2011.

METHODS

This study seeks to compare (1) the volume of the total shoreface sand reservoir as determined using seismic-reflection data, and (2) coastline evolution over the past 62 years, determined from six sets of aerial photographs (1949, 1978, 1985, 1990, 2000 and 2005; © IGN, Institut Géographique National) and modern shoreline positions mapped using differential-GPS. All data were acquired and processed in the WGS-84 geographic projection and coordinates were calculated in planar projection UTM zone 21N.

Approximately 115 km (corresponding to 64 profiles, Fig. 2.A) of seismic-reflection data were acquired in 2011 using a 4-12 kHz bi-frequency INNOMAR seismic sounder fixed at 6 kHz. Surveys extended offshore to the limit of sedimentary cover. Seismic profiles were processed (tide correction, wave filter and amplitude correction) and the interpretation was digitized (seafloor, contact between unconsolidated sediment and underlying bedrock) using ISE V.2.92 software. The sedimentology of seafloor deposits (the uppermost unconsolidated sediment unit) was investigated with a series of 64 surface samples collected along 10 shore-normal transects (Fig. 2.A). Images from the 2005 aerial photography survey were used to identify shallow-water rock outcrops that did not fall on seismic track lines (Fig.2). A 20-m square-elementary-cell-size digital elevation model (DEM) of the shoreface sand thickness was created in ArcGIS v.9.3 through natural-neighbor interpolation. In this manner, the surface and volume of the sand reservoir were also estimated. The error associated with estimates of the sand unit thickness is a function of the precision of the digitalization and is estimated at ± 10 cm. Volume error was determined by multiplying the three-dimensional area of the sand unit and the vertical error associated with seismic mapping.

Each aerial photograph was scanned at high resolution (0.7 m pixel size) and georeferenced (± 2 pixels positioning error) using ArcGIS v.9.3. The definition of shoreline positions from aerial photographs was obtained using the vegetation line, the suggested method for use in this kind of environment, in light of the associated variable temporal and spatial scales (Boak and Turner, 2005). Along heavily-anthropogenically-influenced sections (Fig. 2.C), the foot of breakwater was chosen to delimit the shoreline position. Shoreline position accuracy is estimated at ± 3.5 m (georeferencing error added to ± 3 pixels shoreline digitalization error). The 2011 shoreline position was acquired using a Magellan-Ashtech kinematic differential GPS (D-GPS). Data were collected at 1 m intervals with 5 cm accuracy (XYZ) along the vegetation line. Shoreline change (erosion, stability or accretion) during each time interval was calculated at 50 m intervals along the entire barrier shoreline using the Digital Shoreline Analysis System (DSAS) extension for ArcGIS.

RESULTS

Identification of seismic units

Two different units are identified in seismic profiles (Figs. 2.A, 3): a basal unit and a surficial unit. The basal unit is characterized by chaotic internal reflections in seismic profiles and displays a rapid loss in signal amplitude with depth penetration. The exact nature of this unit is difficult to determine, but the highly irregular erosional surface of the top of this unit suggests that it is predominantly rocky outcrops discontinuously overlain by gravel moraine. Bedrock and moraine are combined into a single unit (acoustic bedrock, Fig.3). Combining these two lithologies has no effect on this study, nor on the volume calculations of the overlying unit. The contact between the basal unit and the surficial unit is visible on all profiles due to the high impedance contrast between acoustic bedrock and the overlying sediment. The upper unit is characterized by a transparent seismic facies and a sand-sized texture in bottom grab samples. This unit is herein referred to as the Upper Sand Unit (USU, Fig. 3).

Characterization of the USU reservoir

The USU covers an area of 22 km² of the shallow shelf seaward of the west side of the barrier. Its depth and thickness (Fig. 2.B) are highly variable and closely related to the topography of the acoustic bedrock unit. The thickness of the USU does not exceed 3 m and is, on average, between 1 and 2 m (Fig. 2.B, 3). The volume of this unit has been calculated as $(15 \pm 2) \times 10^6$ m^3. It can be spatially sub-divided into three sectors (Fig. 2.B). From north to south, these are:

- The northern sector (A) is characterized by the presence of rocky outcrops on shallow (5-10 m depth), high-relief (2 m high) sections that are located within 100-200 m of the shore. Here, the sand reservoir (USU_A) extends out to 1-1.5 km offshore (up to 13 m depth contour) and the shoreface slope is 1%.
- The middle sector (B) is characterized by the absence of rocky outcrops on the shoreface. Here, the sand unit (USU_B) extends out to 2-2.5 km offshore (to the 17 m depth contour) and the shoreface slope is 0.7%.
- The southern-most sector (C) is characterized by the presence of rocky outcrops on shallow (5-10 m depth) sections, albeit further offshore (650 to 850 m) as compared to those found in USU_A. Here, the upper sand unit (USU_C) extends out to 2-2.5 km offshore (to the 17 m depth contour). The shoreface slope is 0.6%, similar to USU_B.

The three sand units, USU_A, USU_B and USU_C have volumes of (600 ± 100), (1500 ± 200) and (1300 ± 200) m^3/per linear meter alongshore (lm), respectively. Sectors B and C contain roughly equivalent volumes of sand per lm; Sector A contains less than half that volume per lm of coastline. Hence, the shoreface sand reservoir is unequally distributed and is most densely concentrated along the middle and southern sectors of the island. As such, Sector A is relatively sediment starved in relation to the rest of the barrier.

Seafloor sediment samples from all three sectors are unimodal, centered at 0.125 mm, and have a median grain size of 0.16–0.125 mm. However, variations exist between samples from the upper and lower shoreface: shore-proximal samples contained a relative excess of coarse sediment (0.6-0.16 mm size interval, negative asymmetry), whereas offshore samples were generally finer and positively asymmetric. Locally, on Sectors B and C and near the contact with bedrock, samples show bimodality at 0.125 mm and a second coarse mode at 0.25 mm.

Shoreline migration

The west coast of the Miquelon-Langlade Barrier shoreline has demonstrated periods of retrogradation, relative stability and progradation between 1949 and 2011. From north to south, four areas can be distinguished. The first one is a 3.3-km-long section of coast that has experienced 25-45 m of retrogradation over this period (Fig. 2.C). Retrogradation was not constant, but rather occurred primarily during two periods: 1985-1990 and 2005-2011. These time periods were also characterized by more frequent high-energy events (storms) that induced landward shoreline migration of up to 30 m (Robin, 2007). Today, this section of coast is composed of vegetated dunes, the front of which often contains a 1-2-m-high scarp. Erosion at the front of the dune, and internal aeolian sediment reworking, have resulted in destabilization of the dune and consequent shoreline transgression. By contrast, immediately to the south, a 2.3-km-long section of coastline has experienced net progradation of 5-35 m (Fig. 2.C). This occurred almost exclusively between 1949 and 1978 and it is entirely due to road construction along the upper part of the beach. The positioning of this road proximal to the natural shoreline position has required the subsequent installation of road protection along the beach. The third section of coast, in the central portion of the coastline, is 2.8 km long and has undergone low amplitude migrations (± 7 m migration) over this study period (Fig. 2.C). This stability is observed during the entire study period and between each time slice. The last, southernmost, area is a 3.6-km-long section of coastline that has experienced 5-20 m of progradation (Fig. 2.C). Progradation has occurred at a gradual rate of 0.1 to 0.3 m/yr during the period of 1949-2011. No singular progradational event can be identified. A north-south gradient is apparent across these four sections of the coast, with retrogradation in the north, stability in the center and progradation in the south.

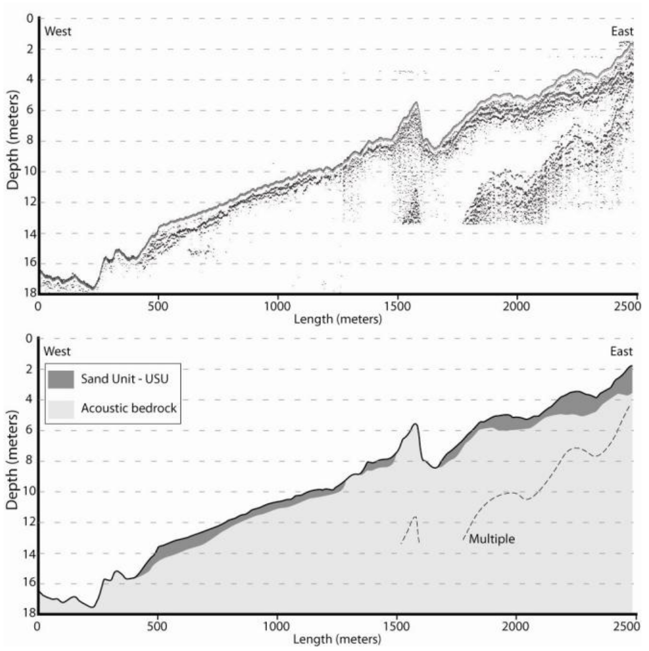

Figure 3. Raw (top) and interpreted (bottom) seismic profile (Profile_50), collected along an east-west transect, offshore of the southern section of the Miquelon-Langlade Barrier (see Fig. 2a for location). Hydrographic zero is equal to 1.26 m altitude. Dark and light gray shading in the interpretation represents sandy (USU) and rocky (Acoustic bedrock) units, respectively.

DISCUSSION

Correlation of shoreface-shoreline evolution

The results of these analyses provide evidence of spatial variability of the extent and volume of the shoreface sand reservoir, with a significant dearth of sediment to the north and more sediment to the middle and south, and a north-south gradient in the multi-decadal shoreline evolution (Fig.2). In the northern part (Sector A), the shoreline is in retrogradational state and USU_A (m^3/lm) is the smallest along the barrier. In the central and southern parts (Sectors B and C) the shoreline is stable or prograding. The volumes (per lm) of USU_B and USU_C in each of these regions are more than double that of Sector A. Thus, a gross correlation seems to exist between shoreline evolution at multi-decadal scales and the relative volume (per linear meter alongshore) of the shoreface sand reservoir.

Conceptual scenarios of former and current sediment transport patterns

The remobilization of morainal deposits, outwash sands and sediments deposited during stable, lower stands of sea level (11000-8000 yr. BP at -25 m in this area; Forbes and Syvitski (1994)) by hydrodynamic processes (Fig. 4) provided sediment for barrier construction. This occurred as the result of two convergent progradational systems. Evidence for this evolutionary history is still apparent throughout the barrier; for example, relict recurves on the northern part of the barrier show evidence of southward sediment transport and progradation of a barrier spit (Fig. 4). Furthermore, these morphologies provide evidence that the former barrier was once positioned further offshore than at present.

Modern transport patterns along the barrier are similar to those inferred from the relict morphologies, and correspond to a bi-directional longshore transport regime (Robin, 2007) that converges in the narrow central part of the barrier (southern part of Sector B; Figs. 2, 4). Robin (2007) documented similar alongshore sediment-transport variation: higher rates of transport along the northern section, very low along the narrow-central part of the barrier (likely due to the swash orientation of the shoreline), and intermediate (~15 % of that in the north sector) along the southern sector. Furthermore nowadays, sediment delivery by the longshore transport system is reduce due to the lack of appropriate sediment reservoirs from which this sediment could be derived: till deposits to the north and south of the barrier contain little sand-sized sediment and outwash sediment reservoirs have been naturally depleted.

Even if longshore transport appears like a key parameter, cross-shore sediment transport could have also played a significant role in sediment delivery, especially on the middle part of the west coast of the barrier. This is evinced by the coarsening of sediment from the lower shoreface to the beach and by the presence of relict progradational beach-ridge system (Figs. 2.C, 4). As such, the sandy sediment reservoir along the shoreface likely provided one of the sand sources for feeding the beach ridges and foredune systems.

Parameters driving the current evolution of the system

Sector A has the steepest shoreface slope (1%) of the study area and is the region with the greatest exposure to high wave energy. As consequence, sediment can be remobilized further offshore. Additionally, this sector receives little sand-sized sediment via longshore transport of sediment eroded from the proximal, but sand-poor moraines, which are dominated by pebbles, granules and clays. The result is a less spatially-expansive sand reservoir on the shoreface (the boundary between sand and exposed rock is at only 13 m depth; Fig. 2). Furthermore, this section of coast is primarily drift-aligned, receiving a more oblique wave approach; as such, waves tend to transport sand-sized sediment further alongshore, out of this sector, than is possible along the other, swash-aligned sectors of the coast. Combined, these factors leave this northern-most sector depleted of sand, resulting in a retrogradational shoreline on the Buttereaux sand dunes area.

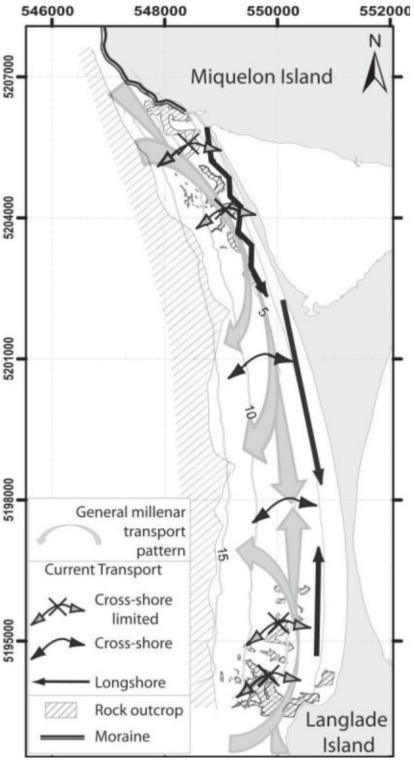

Figure 4. Schema of the transport pattern (former and current) along the west coast of the Miquelon-Langlade Barrier.

Along Sector C, wave energy is minimized by protection from a bedrock/till cape to the south (Langlade Island), and by dissipation of energy due to a gentler slope (0.6%) and shallow subaqueous bedrock outcrops. These factors combine with a larger shoreface reservoir to induce net northward sediment transport. However, this occurs at a slow enough rate that this sector of coast experiences a net sediment surplus, resulting in slow progradation of sandy foredunes.

Sector B is located where the two longshore sediment transport regimes decrease and converge. Despite the availability of abundant sand on the shoreface, slow rates of sediment transport induced insignificant shoreline migration at the timescale of this study; thus, foredune position has remained stable during the past few decades.

It should be noted that underlying geology plays a crucial role in these observed trends. Foremost, the shallower rock outcrops likely played an important role in the formation of the barrier by serving as a pinning point for migrating sediments. At present, the slope of the underlying (and subaqueously-exposed) bedrock on the shoreface serves to influence the shoreface slope, provides a first-order control on wave energy and available accommodation for sand on the shallow shoreface. Thus, the underlying geology continues to play an important role in sediment transport and wave processes (wave breaking, wave attenuation etc.; e.g., Jackson, Cooper and Del Rio (2005)). Cross-shore sediment exchange from the lower to upper shoreface is also limited by the distribution of shallow bedrock outcrops that are commonly found in 5-10 m water depth and extend up to 2 m above the surrounding sea floor in Sectors A and C (Figs. 2, 3). Likewise, these outcrops partially control longshore sediment transport, notably in sector A where they are shallower and occur very close to shore (100-200 m).

Miquelon-Langlade Barrier in Context

Correlations between shoreface sediment reservoirs and shoreline variability have been observed in Languedoc-Roussillon (Mediterranean coast, Gulf of Lions, France;Certain *et al.* (2005)). Further evidence between shoreface and shoreline migration has also been observed along the Fire Island coast (Long Island, New York, USA). The shoreface sediment budget here is influenced by the presence of long ridges of sediment discontinuously present along much of the shallow shelf (Schwab *et al.*, 2000).

Despite significant differences between these sedimentary environments and the Miquelon-Langlade Barrier, the sedimentary reservoir volume is closely related to the shoreline evolution in the past few decades, especially along the retrogradation area, due to a depleted shoreface sediment stock.

CONCLUSIONS

The west coast of the Miquelon-Langlade Barrier is geologically controlled by the shoreface slope, and the presence of shallow till and subaqueous bedrock outcrops. Due to inadequate external sediment sources (i.e., till outcrops on proximal islands), the state of the shoreline (retrogradation, stable, progradation) is closely related to the volume of the adjacent shoreface sedimentary reservoir. This relationship is especially prevalent along the retrogradational northern part of the Miquelon-Langlade Barrier.

The size of the offshore sediment reservoir is a typical parameter used to explain the formation and evolution of a given coastal system over long (> 100 years) time scales (Stive *et al.*, 2002). This parameter is less commonly regarded in multi-decadal scale studies, which tend to focus almost exclusively on hydrodynamic processes and shoreline evolution. In conjunction with shoreline-monitoring studies and knowledge of transport patterns, the volume of shoreface sediment available to feed the barrier may provide a good alternative proxy. This proxy has a strong potential for widespread applicability; however, future similar studies of other similar systems are needed.

This study of shoreface-shoreline sediment exchange along the west coast of the Miquelon-Langlade Barrier is part of a larger study focusing on the complex construction of this barrier that contains a number of morphological features (spits, aeolian dunes, a lagoon, ponds, and a complex beach-ridge system). The understanding of transport patterns (both former and modern) and the role of the geological controls are essential to reconstruct the history of the barrier formation and predict its future evolution.

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