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Dominance of Inherited Geologic Framework on the Development of Coastal Barrier System

Julie Billy[†], Nicolas Robin[†], Christopher Hein[‡], Duncan FitzGerald[§] , and Raphaël Certain[†]

[†] CEFREM, UMR CNRS 5110
Université de Perpignan Via Domitia
Perpignan, France

[‡] Virginia Institute of Marine Science,
College of William & Mary Department
of Physical Sciences
Gloucester Point, USA

[§] Boston University, Department of
Earth and Environment,
Boston, USA

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ABSTRACT

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Many coastal systems are influenced by geologic framework (*e.g.*, bedrock or inherited sedimentary systems), either in their initial development, morphology, or continuously throughout their evolution. This study adds to our understanding of the role of bedrock inheritance by describing the evolution of the Miquelon-Langlade Barrier (NW Atlantic; France). This barrier has a complex coastal planform (Y-shape, 12-km-long, 100-2500-m-wide) with several embedded sedimentary landforms. Ground-penetrating radar and HR seismic data collected along the subaerial and subaqueous portions of the barrier reveal: (i) the bedrock architecture (largely buried by Holocene deposits) and (ii) the presence of specific inherited sedimentary units. Indeed, both the location and early development of the barrier are largely controlled by bedrock morphology; the barrier is perched on a buried bedrock high in its center, and pinned to subaerial bedrock exposures at its northern and southern ends. Moreover, unconsolidated sedimentary shoals, formed and modified by waves and tides during earlier stages of rapid sea-level rise, provided important morphological constrains that influenced barrier development and the resulting complex morphology of the barrier and associated beach-ridge plain. This study demonstrates the utility of using coupled terrestrial and marine geophysical data to map geologic framework units, thereby determining the role of inherited geology in the evolution of coastal systems.

ADDITIONAL INDEX WORDS: *Coastal geomorphology, Geologic framework, Internal sedimentary architecture, Ground-penetrating radar; High-resolution seismic profiling.*

INTRODUCTION

Geologic framework (*i.e.*, bedrock, antecedent topography, inherited sedimentary units) plays a crucial role in determining barrier location and the morphology of associated nearshore and coastal deposits (Riggs, Cleary and Snyder, 1995). For example, antecedent substrates can serve as pinning points to stabilize landward-migrating barriers, thus aiding their stabilization and seaward progradation (Evans *et al.*, 1985). Nearshore wave patterns and sediment transport are also directly influenced by subaerial and submarine features, which can explain the origin, morphology, and evolution of some coastal systems (Lentz and Hapke, 2011; Riggs, Cleary and Snyder, 1995).

Relationships between geologic framework and coastal features are well known for barrier-island systems (e.g. Lentz and Hapke, 2011; Riggs, Cleary and Snyder, 1995; Schwab *et al.*, 2014; Schwab *et al.*, 2000), but poorly investigated for composite coastal barrier systems, such as tombolos, complex spits, and welded barriers.

The study demonstrates how geologic framework, both bedrock and antecedent sedimentary deposits, largely determined the location, gross stratigraphy, and morphology of the composite Miquelon-Langlade Isthmus barrier system.

STUDY SITE

The Saint-Pierre-et-Miquelon Archipelago (France) is located in the northwest Atlantic Ocean, 50 km south of Newfoundland (Canada). This archipelago is the emerged summit of Miquelon bank (Figure 1A), a vast bedrock area disconnected from Newfoundland and surrounded by deep (140 m) channels. It is composed of three bedrock islands, (i) northern Miquelon Island, (ii) Langlade in the south, and (iii) Saint-Pierre in the southeast. Miquelon and Langlade are linked by a 12 km long, 50- to 2500- m wide, Y-shaped isthmus (Figure 1B). The sediment source, formation, and evolution of this barrier are tied closely to the latest episode of Pleistocene glaciation. Ice retreated from this archipelago by 13–12 ka, and since that time glacial deposits have been eroded and reworked by waves and tides under conditions of relative sea-level (RSL) rise (Billy *et al.*, 2015) to form a complex mixed-sand-and-gravel composite barrier. OSL age data of the barrier and a late-Holocene RSL have been published in Billy *et al.* (2014) and Billy *et al.* (2015), respectively.

The northwestern section of the barrier contains a narrow (50–200 m wide) and high (up to 15–20 m) parabolic dune system, called "Les Buttereaux." Its northeastern section is composed of a sandy, mainland-attached re-curved spit that terminates at its southern end at an active tidal inlet. This inlet connects Grand Barachois Lagoon (area: 12 km²) to the coastal ocean. The central and southern sections of the barrier consist of a

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*Corresponding author: juliebilly@gmail.com

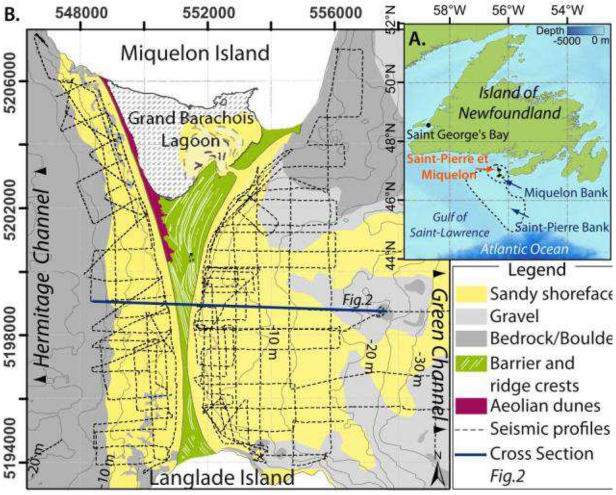

Figure 1. A) Location map of the Saint-Pierre-et-Miquelon Archipelago (NW Atlantic). B) Map of the Miquelon-Langlade Barrier, seismic profile locations (gray dotted lines), and shoreface type: bedrock / boulder/, gravel or sand.

well-developed beach-ridge plain that reaches a maximum elevation of only a few meters above mean sea level (msl), and is fronted by a modern foredune ridge. The plain is composed of two, distinct, opposing beach-ridge systems, consisting of six major beach-ridge sets (U_A – U_F). Four concave ridge sets (U_A, U_C, U_E and U_F) define the eastward-prograding system (S_E), with a combined area of 3.8 km^2. Two linear ridge sets (U_B and U_D) define the south-westward-prograding system (S_W), and have a combined area of 1.1 km^2 (Billy *et al.*, 2014, 2015).

METHODS

The geologic framework was mapped from geophysical data gathered along the shoreface and beneath the subaerial barrier.

The internal architecture of the barrier was investigated using a Mala ProEx ground-penetrating radar (GPR) system with a 100 MHz antenna coupled with a survey wheel and a Magellan-Ashtech RTK-GPS (12.5 km of data). This antenna can image at 0.15 m resolution down to ~12 m below the surface, although signal loss generally occurred between 9 and 12 m depth. Of particular importance in this study was the basal unit found below beach-ridges deposits (Billy *et al.*, 2014).

Shoreface architecture was investigated using very high-reflection (VHR) seismic data that was acquired with a 4-12 kHz bi-frequency INNOMAR seismic sounder, fixed at 6 kHz (Billy *et al.*, 2013). Seismic-reflection data were acquired along both the west and east sides of the barrier (115 km and 215 km, respectively). The maximum depth of penetration in unconsolidated sediment was 10 m below the sea floor.

The chronological context of the barrier formation is known from OSL dating published in Billy *et al.* (2015) and furthered analyzed in Billy (2014).

RESULTS

Bedrock or inherited sedimentary units are identified below the current barrier either along the shoreface (bedrock) or below beach-ridges deposits (BU_1-BU_3).

Bedrock -Shoreface

Bedrock is highly distinguishable in seismic profiles from sedimentary deposits due to its rugged surface signature (Figure 2). Along the western side of the barrier, bedrock is covered by a thin (1-2 m thick) sand unit that is exposed in shallow outcrops (5-10 m depth; 2 m height) on both its northern (100-200 m offshore) and southern sectors (650-800 m offshore) (Billy *et al.*, 2013). Along the east side of the barrier, bedrock forms both a basin with a central depression (~25 m below msl) and seafloor surface outcrops (up to 10 m high; Figure 2; Billy, 2014). Bedrock also forms a north-south oriented ridge connecting Miquelon and Langlade Islands.

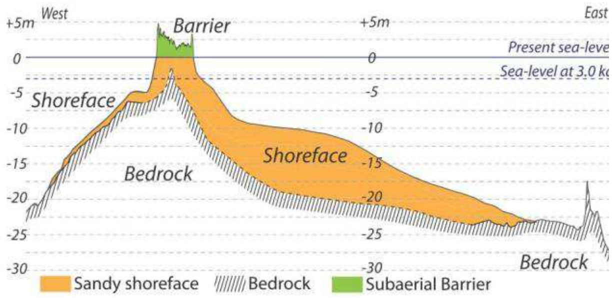

Figure 2. Interpreted cross-section of central Miquelon-Langlade Barrier, illustrating sedimentary units deposited atop bedrock

Basal units (BU_1 –BU_3)

Basal units are observed in GPR profiles (Figure 3) in three distinct areas. No physical connection could be established among these units, and therefore are treated as three distinct units: BU_1, BU_2, and BU_3. Basal units are not sampled or cored, thus the sedimentary nature of these units cannot be determined.

BU_1 is visible across 350 m at the northwest part of the ridge plain (Figure 3A-B), reaching a thickness of at least 2.5–3.0 m. BU_1 has moderately continuous to discontinuous, sigmoid–oblique-shaped internal reflections with moderate signal intensity. Internal reflections in this unit dip in opposite directions: westward at 3.0–3.6° along 200 m of this profile and eastward at 3.5° along 150 m of this profile. Its upper boundary (L_A) shows smooth, erosional truncation with top-lapping reflections, and dips gently (0.6°) to the east (Figure 3B).

BU_2 is visible for 100 m in the central part of the plain (Figure 3A-C). It is characterized by a chaotic reflections and poorly defined underlying reflections. BU_2 forms a subsurface topographic high and is interpreted as bedrock ridge (shallowest point at -1 m msl). The upper boundary (L_D to the west; L_E to the east) is continuous and has a strong amplitude signal. Elsewhere BU_2 is either not visible due to saltwater attenuation (eastward) or its signature is limited by radar signal attenuation (westward) (Figure 3 C).

BU_3 is imaged locally (100 m wide, 700 m long) where both U_C and U_E originate (Figure 3A-D). BU_3 is characterized by near-horizontal internal reflections (<1° eastward-dipping) in a cross-shore direction and by northward-dipping internal reflections (up to a 9° dip-angle) observed in shore-parallel transects (Figure 3D). It has a smooth, likely erosional, upper boundary (L_E) which reaches to −2 m msl.

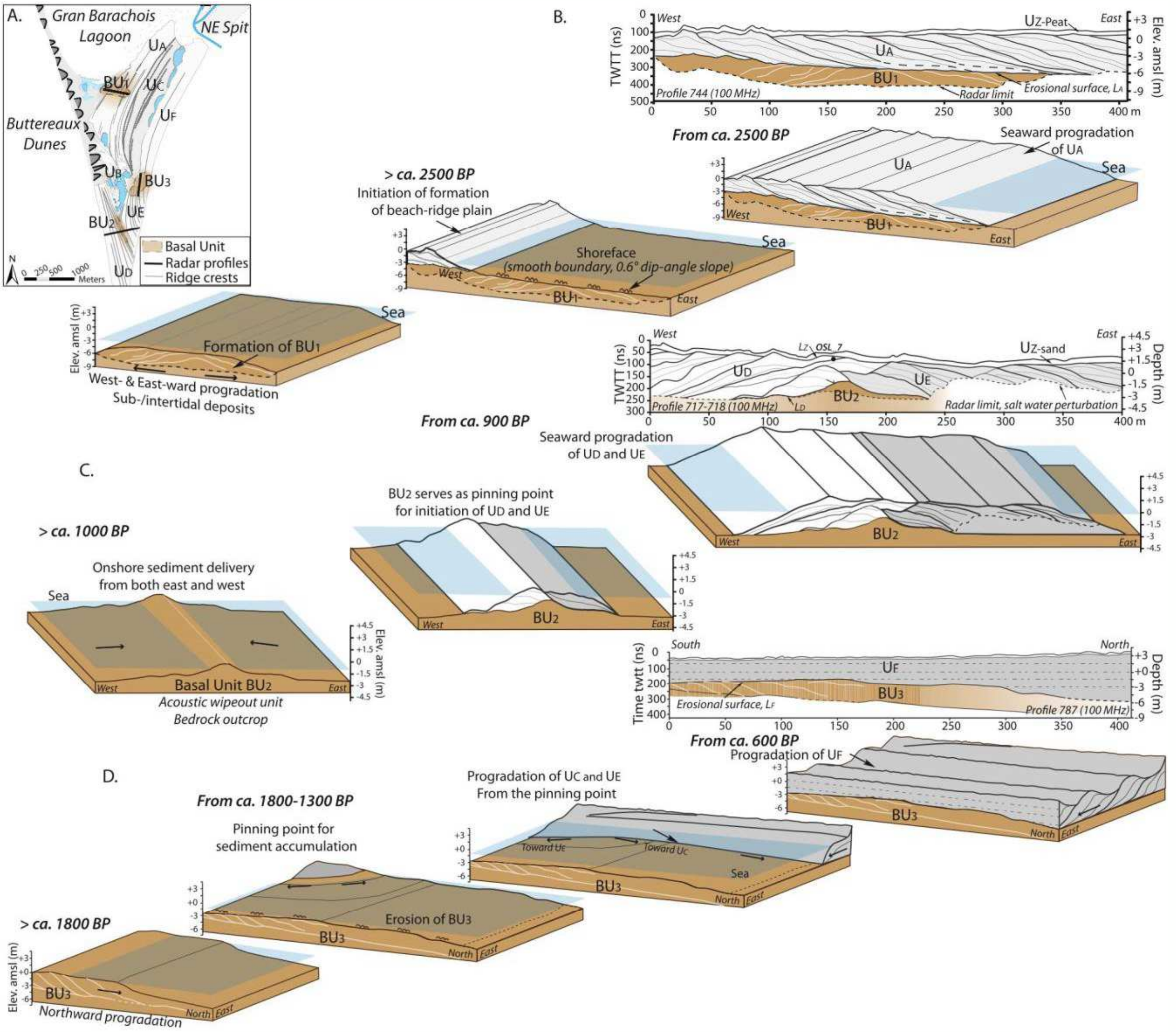

Figure 3. A) Location map of radar profiles and basal units (in brown) across the beach-ridge plain (units U_A-U_F; in gray). Interpreted radar profile and 3D evolutionary model are shown for each basal unit, B) BU_1, C) BU_2, and D) BU_3.

DEVELOPMENT OF THE BARRIER AND LINKS WITH GEOLOGICAL FRAMEWORK

Primarily bedrock control (8.0-3.0 ka)

South of Newfoundland, the marine transgression occurred during the early to middle Holocene (8.0–3.0 ka) and was defined by rapid RSL rise from -25 m to -3 m (rate: + 4.4 mm/yr) (Bell *et al.*, 2003; Forbes, Shaw and Eddy, 1993). In response, a subaerial bedrock ridge that once linked Miquelon and Langlade Islands was progressively flooded between 5.0 and 4.0 ka. During the following period of slow RSL rise (5.0-3.0 ka), a mixed sand and cobble barrier formed that was pinned along the southwest side of Miquelon Island (Figure 4A). Shallow bedrock, currently buried by sediment 6 to 8 m below msl (Billy *et al.*, 2013) likely contributed to the early formation of the barrier system by providing a pinning point for sediment accumulation. This rocky outcrop was quickly submerged by rising RSL and later buried by the barrier. The bedrock outcrop defined the locus of sediment deposition and the north-south alignment of the overlying composite barrier system. The early nearshore likely contained scattered bars, banks, or shoals.

Formation and development of the barrier and its associated nearshore deposits were likely fed from sediment eroded from extensive nearby glaciogenic deposits and driven onshore and alongshore by constructive waves. The marine transgression in response to rising RSL drove the proto-barrier landward toward its current position. To the south, a relict nearshore or intertidal shoal is preserved as basal unit BU_1 (Figures 3B, 4A). This shoal, imaged in GPR transects, prograded both westward and eastward; Figure 3B). GPR records suggest that it was being actively

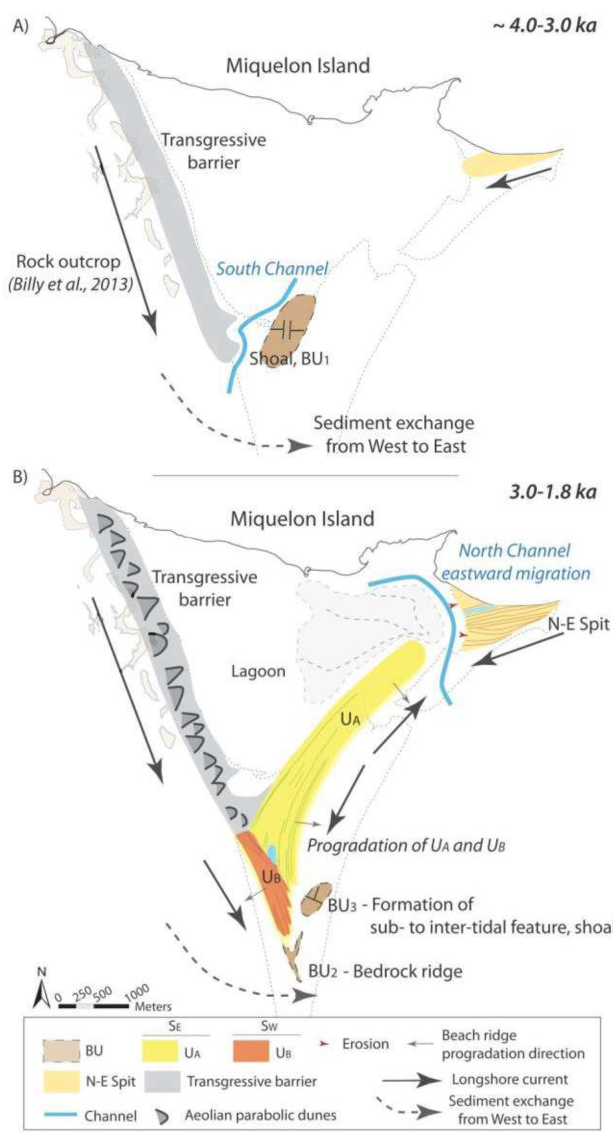

Figure 4. Evolutionary model of the barrier A) at 4.0-3.0 ka, illustrating the primarily influence of bedrock substrate on its development; B) from 3.0 to 1.8 ka, illustrating the influence of inherited sedimentary units (BU_1, BU_3) and the bedrock ridge (BU_2) on beach-ridge plain development. Light gray, dashed lines correspond to the position of the modern barrier.

reworked on both its eastern and western sides, indicating that BU_1 was separated from the proto-barrier. It is proposed that these accretionary features were originally separated by an inlet (South Channel, Figure 4A), the vestiges of which are defined by the presence of a topographic depression at the site (partially flooded and filled with peat).

Inherited sedimentary unit influence (3.0-1.8 ka)

During this period, the rate of RSL rise decreased to +1.3 mm/yr. The proto-barrier continued its southwesterly elongation, eventually leading to the closure of the southern inlet. BU_1 was partially eroded (Figure 3B). The proto-barrier and inherited sedimentary unit BU_1 played an important role in the early development of the first beach-ridge unit (U_A); this ridge set formed in an area protected from energetic westerly Atlantic swells by the southerly-elongating barrier to its west, and is pinned to BU_1. U_B formed broadly during the same period, appending to U_A and prograding westward to form a set of linear, shore- parallel to sub-parallel beach ridges.

At this time, the two islands were still not connected. Coastal systems attached to each island were separated by a 3.0–3.5-km wide tidal inlet. Tidal and wave-generated currents flowed through this inlet, allowing the transfer of sediment from the west to the east side of the barrier (highlighted in analyzed shoreface bathymetry and seismic data; Billy *et al.* (2013) and Billy (2014)). Basal unit BU_3 (Figures 3D, 4B) is interpreted as an intertidal shoal, and displays evidence of northward progradation (northward-dipping internal radar reflections). It was influenced and shaped by currents and wave action proximal to this central inlet.

Units U_A and U_B continued prograding in their respective directions until about 1800 yrs BP (Figure 4B). A change in ridge-crest orientation is visible in the southern region of U_A, accentuating the concave planform shape of this unit. This morphology is attributed to wave diffraction and refraction around the intertidal to subaqueous unit BU_3 (Billy *et al.*, 2014), thereby driving sediment deposition patterns, and producing the curvature observed in the modern curved planform morphology of unit U_A (Figure 4B).

Central barrier development (1.8-0.8 ka): Influence of bedrock and the basal sedimentary unit

Along the east coast of the barrier, the upper portion of BU_3 was eroded during this period (Figure 3D). The beach-ridge plain was partially pinned to this subaqueous to intertidal bar. It continued to prograde, forming arcuate unit U_C with ridges building in a northeastward direction (as a continuation of U_A; Figure 5). These ridges have a higher elevation and a topography characterized by more visibly rhythmic ridges and swales than unit U_A (Billy *et al.*, 2014).

At the southern end of the plain, southerly longshore sediment transport drove sediment accumulation proximal to basal unit BU_2, which is interpreted as a bedrock ridge (Figures 3C, 5). Later during this stage, beach-ridge units U_D and U_E, both partially pinned to BU_2, began prograding, U_D to the west and U_E to the east (Figure 3C). On the eastern side of the plain, unit U_E built between BU_2 and BU_3 (Figure 5). Based on their respective planform morphologies and stratigraphic relationships observed in radar profiles (Figure 3C), it is assumed that the initiation of progradation of U_E was penecontemporaneous with that of U_D.

Toward the current barrier

Relative sea level continued to rise to its modern elevation during the last 800 years. Consequently, older and lower beach ridges (U_A and U_B) were gradually flooded during this period. Flooding of lower topographic units led to the deposition of finer sediments in these lowland areas and colonization by halophytic

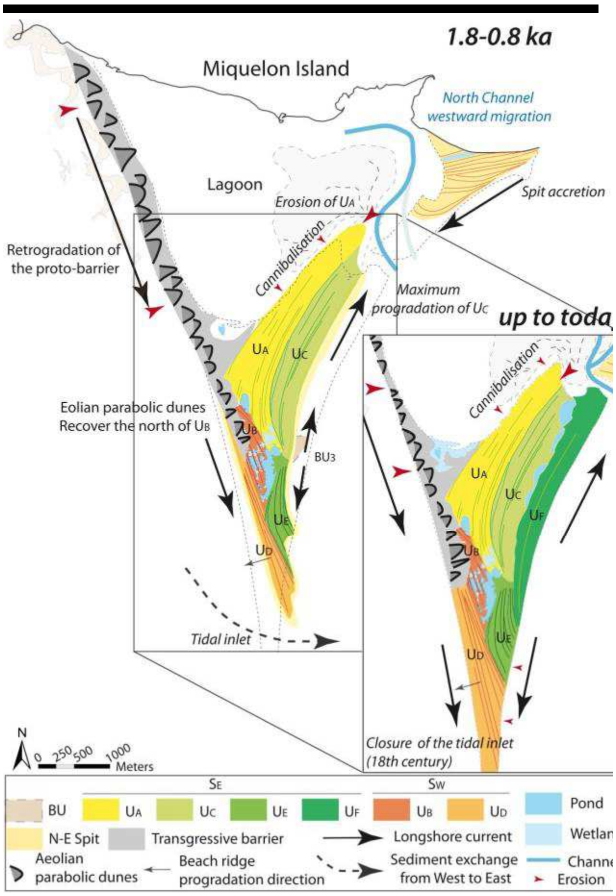

Figure 5. Evolutionary model of the barrier from 1800 to today illustrating the influence of antecedent topography (BU_3).

plants, the development of peats, and cannibalization of U_A from its lagoon (north) side (Figure 5). Along the west coast, the N-W-oriented proto-barrier was overlain by parabolic dunes and continued to retrograde and thin. Southward progradation of the northern recurved-spit complex caused a southwestward migration of North Channel to its current position. This resulted in erosion of the northeastern section of the beach-ridge plain. In the southern section of the plain, units U_E and U_D continued prograding seaward, and beach-ridge unit U_F has prograded seaward of U_C and U_E (Figure. 5).

Closure of the central tidal inlet occurred in the late 18th century (Aubert de la Rüe, 1951; Fortin, 1782), resulting in the formation of a single, thin, curvilinear isthmus that connected Miquelon and Langlade Islands.

CONCLUSIONS

The initial formation, location, and development of the Miquelon-Langlade Barrier were all largely influenced by geologic framework, both local bedrock and inherited sedimentary deposits. Coupled terrestrial and marine geophysical mapping of geologic framework allows for the documentation of the following influences:

- Bedrock morphology affected both the location and early development of the barrier. Indeed, the barrier is perched on a buried bedrock high at its center (the proto-barrier and beach ridges are pinned to the bedrock ridge BU_2), and is pinned to subaerial bedrock exposures (headland) at its northern and southern ends (Miquelon and Langlade islands).
- Inherited sedimentary units influenced the unconsolidated sedimentary units (BU_1, BU_3 - shoals) that were formed and modified by waves and tides during earlier stages of rapid RSL rise, and provided important morphological constrains that dictated barrier development and the resulting complex morphology of the barrier and its associated beach-ridge sets.

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