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Insight into the late Holocene sea-level changes in the NW Atlantic from a paraglacial beach-ridge plain south of Newfoundland

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ABSTRACT

Constructional sedimentary features can provide insight into past changes in relative sea-level (RSL) in regions where traditional bio-stratigraphic markers are absent. The paraglacial beach-ridge plain at Miquelon-Langlade, located 50 km south of Newfoundland, is an example of a well-preserved regressive barrier. Initiation of this plain correlates with a decrease in the rate of RSL rise (from +4.4 mm/yr to ~1.3 mm/yr) at around 3000 years ago. It developed under conditions of normal regression during a period of slow RSL rise (<1.3 mm/yr). The barrier is composed of two oppositely prograding mixed sand-and-gravel beach-ridge systems, which evolved contemporaneously along two open coasts. The growth of these features reflects high rates of sediment influx that was sourced from the erosion of proximal glacigenic sediment (moraines) and reworked alongshore and across-shore by wave action. The combination of stratigraphic (ground-penetrating radar and sediment cores), topographic (RTK-GPS) and chronologic (optically stimulated luminescence, OSL) data provide a detailed understanding of the constructional history of the plain. The well-defined contact between coarse-grained, wave-built facies and overlying aeolian deposits is used to demonstrate the dominant influences of RSL change in the development of the barrier system and produce a RSL curve over the period of its formation. A net increase of 2.4 m in the surface elevation of wave-built facies is observed across the plain, corresponding to the increase in mean sea-level during its formation. Coupled with OSL dates, trends in elevation of the wave-built facies across the plain are used to reconstruct the relative sea-level history during this period. Acknowledging the uncertainties inherent in the method applied in this study, three distinct periods of sea-level rise can be distinguished: (1) an increase from 2.4 to 1 m below modern MSL between 2400 and 1500 years (average rate of +1.3 mm/yr); (2) relatively stable or slowly rising RSL (<+0.2 mm/yr) from 1400 to 700 years; and (3) a rise of ca. 0.7 m during the past 700 years (+1.1 mm/yr). This study not only produces the first RSL reconstruction for the Saint-Pierre-et-Miquelon archipelago but also provides: (i) additional details of RSL changes in a region exhibiting great spatial variations in RSL histories (Newfoundland); (ii) field confirmation that wave-built/aeolian stratigraphic contacts in beach ridges can provide a powerful tool for sea-level reconstructions in mixed clastic systems; and (iii) evidence that sediment influxes can outpace the rate of accommodation creation producing a broad, progradational coastal system.

1. Introduction

Knowledge of past relative sea-level (RSL) changes is crucial for understanding drivers of past coastal evolution and possible impacts of future, climate-change-driven RSL changes on coastal systems. Regressive barriers and beach-ridge systems, prograding coastal features formed when sediment accumulation rates exceed creation of accommodation (vertical space available for sediment) by RSL changes (Galloway and Hobday, 1983; Davis and FitzGerald, 2004; Bristow and Pucillo, 2006; Timmons et al., 2010), and have the potential to record past coastal responses to environmental change (Stapor, 1975; Otvos, 2000; Guedes et al., 2011; Tamura, 2012). For example, regressive coastal systems have been used to provide insight into Holocene RSL changes (e.g., van Heteren et al., 2000; Rodriguez and Meyer, 2006; Clemmensen et al., 2012; Hede et al., 2013; Hein et al., 2013), changes in sediment supply (e.g., FitzGerald et al., 1992; Brooke et al., 2008; Sanjaume and Tolgensbakk, 2009), climatic changes (e.g., Goy et al., 2003; Allard et al., 2008; Nott et al., 2009) and variations in wave regimes (e.g., Dominguez et al., 1987; Goodwin et al., 2006; Rodriguez and Meyer, 2006).

Beach ridges are relict, semi-parallel wave-built features with highly variable sediment compositions (sand to pebble), and are commonly overlain by aeolian deposits (Otvos, 2000; Hesp et al., 2005). The

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topography of sandy beach ridges is controlled mainly by wave swash excursions during fair-weather conditions, whereas gravel ridge elevations are a function of wave height and surge elevation during storms (e.g., Taylor and Stone, 1996; Tamura, 2012). Assessment of the internal architecture, topography and chronology of individual beach ridges, or beach-ridge sets, is essential to decipher their formation history, estimate their progradation rates, and use this information to provide evidence of paleo-sea-level elevations. Most studies of beach-ridge systems have involved sandy systems (e.g., Anthony, 1995; Bristow and Pucillo, 2006; Tamura et al., 2008) or mixed sand and pebble systems (e.g., Schellmann and Radtke, 2010; Clemmensen et al., 2012; Hede et al., 2013), which formed during forced regressions where individual ridges were preserved onshore as RSL fell and the shoreline prograded. In comparison, few studies have focused on the evolution of coarse beach-ridge systems formed in a regime of RSL rise; notable exceptions include the studies of FitzGerald et al. (1992), Isla and Bujalesky (2000), Engels and Roberts (2005) and Plater et al. (2009). Nonetheless, gravel beach-ridge systems are common across the globe, having been identified in Argentina (Isla and Bujalesky, 2000), Antarctica (Lindhorst and Schutter, 2014), the Gulf of Saint-Lawrence, including along southern Newfoundland (Daly et al., 2007; Billy et al., 2014), and British Columbia (Engels and Roberts, 2005), among others. Studies of the formation and evolution of beach-ridge systems formed under conditions of both forced regression (RSL fall) and normal regression (stable or rising RSL) are necessary to fully understand the diversity of evolutionary models for, and potential paleo-environmental records contained within, beach-ridge plains.

In addition to the insights provided from studies of beach-ridge system formation in response to RSL change, these beach-ridge systems themselves can provide valuable paleo-sea-level information. Several features of beach-ridge plains have been investigated for their potential use in sea-level reconstructions, including their elevation and morphology (Tanner and Stapor, 1971; Goy et al., 2003; Clemmensen and Nielsen, 2010), the internal architecture of the foreshore/upper shoreface interface (Tamura et al., 2008; Nielsen and Clemmensen, 2009; Hede et al., 2013), or the interface between wave-built facies and overlying aeolian deposits (van Heteren et al., 2000; Rodriguez and Meyer, 2006). Rodriguez and Meyer (2006) and Hede et al. (2013) highlight that optimal sea-level markers require high preservation potential (protection again erosion or modification after deposition) and coincide with areas of high deposition rates and prograding shorelines. Although the choice and relevance of these markers are subject of debate, during the past decade, the elevation of the foreshore/upper shoreface interface as a marker of paleo-sea-level elevation has been used with broad success (Tamura et al., 2008; Nielsen and Clemmensen, 2009). However, this type of interface is limited in application, because it may be difficult to determine this horizon in the sedimentologic record. Likewise, RSL reconstructions based on the interface between wave-built facies and overlying aeolian deposits are tenuous as well (Thompson, 1992; Otvos, 1999, 2000; Tamura, 2012). Indeed, the interface between the two facies is often unrecognizable due to relatively homogeneous sediment textures or the structures of deposits themselves (Otvos, 1999, 2000). By contrast, mixed sand-and-gravel beach ridges provide a more easily recognizable interface between coarse wave-built facies (as relict berms) and aeolian sand deposits, and therefore are a more appropriate target for paleo-sea-level reconstructions than their sandy counterparts. Despite the advantage of coarse systems, the potential of this paleo-sea-level marker is not yet proved in sand/gravel systems.

Our study uses the contact between mixed sand-and-pebble wave-built deposits and overlying aeolian sand or peat deposits on the beach-ridge plain of the Miquelon-Langlade Barrier (northwest Atlantic) to investigate RSL trends of this region. Real-Time Kinematic (RTK) GPS topographic surveys, ground-penetrating radar (GPR), sediment cores, and optically stimulated luminescence (OSL) dating are used to examine, in detail, the plain and its evolution over the last 3000 years. Delineation of the interface between wave-built facies and overlying aeolian deposits relies on an exhaustive study of this beach-ridge plain by Billy et al. (2014), which produced a detailed model of ridge morphology and internal architecture of these features. The goal of this study is to combine chronology with detailed topographic and stratigraphic data to examine the potential of this marker on the Miquelon-Langlade mixed beach-ridge systems to record and preserve paleo-sea-level information, and secondly to develop the first RSL reconstruction for this site, which is located in a region exhibiting great spatial variations in RSL histories (Newfoundland). Finally, the late Holocene sea-level curve of the archipelago is compared regionally, and related to the development of the plain.

2. Study area

The Saint-Pierre-et-Miquelon Archipelago (France) is located 50 km south of Newfoundland, Canada (Fig. 1). The formation, evolution, and rate of sediment delivery to the Miquelon-Langlade Barrier are related to the reworking of glacial deposits of the last glacial period by subsequent RSL rise (Robin, 2007; Billy et al., 2014). At Newfoundland, numerical models predicted zones of post-glacial RSL changes ranging from a zone of continuous emergence (Type A RSL changes; Fig. 2A) to the north, to a zone initially emergent then subsiding (Type B RSL changes; Fig. 2A) elsewhere (after Quinlan and Beaumont, 1981). Differences are related to long-term glacio-isostatic adjustment. Indeed, following ice retreat in southwest Newfoundland (13–12 ka; Shaw et al., 2006), four major periods of RSL variation are distinguished at Saint George's Bay (Fig. 2): 1) a period of rapid crustal rebound and falling RSL (+40 to −25 m) at 13.7–10.5 ka; 2) a period of relative stability at ca. −25 m between 10.5 and 8.0 ka; 3) a period of RSL rise between −25 and −3 m at 8.0–3.0 ka; and 4) slow RSL rise during the last 3000 years (Brookes and Stevens, 1985; Forbes et al., 1993; in Forbes and Syvitski, 1994; Shaw et al., 1997; Bell et al., 2003; Daly et al., 2007). During ice retreat, a large volume of sediment (till and outwash) was deposited on the shelf and in the coastal zone in the region of Newfoundland (Fig. 3). For the past several thousand years, coastal processes have reworked these sediments, forming sand-and-gravel barriers, beaches, spits and beach-ridge systems around the Saint-Pierre-et-Miquelon archipelago. The shoreface proximal to the Miquelon-Langlade Barrier is composed of bedrock or glaciogenic and/or paraglacial (derived from the reworking of primarily glacial deposits) gravel (granules to cobbles) and sand, which is more abundant along the eastern side of the barrier (Fig. 3).

The microtidal regime along the archipelago is semi-diurnal with a mean range of 1.4 m at Saint-Pierre. The wave climate is dominated by regular, high-energy Atlantic swell from the west to south, with deep water mean significant and maximum wave heights of 4–5 m and 8.4 m, respectively (based on data from CANDHIS [Centre d'Archivage National de Données de Houle In Situ, http://candhis.cetmef.developpement-durable.gouv.fr]). The dominant wind and wave regime are controlled by extra-tropical cyclonic systems traveling from the eastern United States across the Atlantic toward northern Europe. These storm systems coupled with the expansive southwesterly fetch produce relatively high wave energy along the western shore of the barrier; the eastern shore is largely protected by nearby Newfoundland (Robin, 2007; Billy, 2014). Since the middle of the 20th century, RSL in south Newfoundland has been rising at a rate of +2.5 mm/yr (based on data from PSMSL [Permanent Service for Mean Sea Level, http://www.psmsl.org/data/]) due to the combined effects of rising global sea level and regional crustal subsidence (Peltier, 2004; Koohzare et al., 2008). The Miquelon-Langlade Barrier is a 12 km-long, 50–2500 m-wide, Y-shaped isthmus with a dominant north–south orientation (Fig. 1B). Longshore sediment transport is toward the center of the barrier on both sides, converging in the narrow central region (Fig. 3) (Robin, 2007). The northwestern section of the barrier consists of a narrow (50–200 m wide) and a relatively high (up to 15–20 m)