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Rapid Coastal Dune Migration into Temperate and Equatorial Forests: Optical Chronology of Imaged Upper Slipface Strata

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ABSTRACT

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This study presents the first sets of optical dates that constrain dunefield evolution along a temperate, forested, microtidal barrier (Curonian Spit, southeast Baltic Sea, Lithuania) and a macrotidal equatorial mangrove coast (Pará State, northern Brazil). In both areas, high-resolution geophysical (georadar) images were used to map the subsurface architecture, relative chronology, and orientation of dune migration surfaces (slipfaces) and vertical accretion strata. Besides relative chronology of dune accretion, subsurface images reveal bounding (superimposition) surfaces indicative of distinct activity phases. A cross-barrier Preila transect on the Curonian Spit, served as the basis for establishing dune chronology in this historically active part of the Great Dune Ridge. Due to barrier width (> 1km) and dune height (>30 m), aeolian sand transfer, rather than overwash and breaching, has been the dominant process of landward migration for this barrier spit since mid-Holocene. OSL dating of the upper sections of buried slipfaces in shallow trenches revealed dune migration of more than 600 m between mid-1500s and late 1700s at the Preila site. These ages are consistent with historical records and the time of burial of a coastal village near the edge of a lagoon by 1797. In equatorial Brazil (Atalaia Beach), large reactivated parabolic dunes have been migrating over coastal roads and mangrove forests over at least the past 150 years. In geophysical images of a parabolic dune, numerous high-amplitude hyperbolic anomalies produced by buried trees contrast with steeply landward-dipping slipface reflections. Due to water table elevation, the lower older part of the dune sequence has been stabilized in the blowout area. Similarly, interdunal lake has partially arrested the migration of a transverse dune ridge, while the adjacent segment continues to advance onto a sparsely vegetated plain. Our preliminary data indicate that whereas the two regions differ markedly in their precipitation patterns, vegetation types, oceanographic setting, and land-use history, both experienced episodes of rapid (average: 1-2 m/year) migration of massive dunes (10-50 m high), which continues locally at the present time. Aside from their implications to coastal evolution, accurate reconstructions of dune dynamics on decadal to centennial time scales should be integrated into coastal development and management strategies.

ADDITIONAL INDEX WORDS: *Parabolic dune, Bounding surfaces, OSL, GPR, Brazil, Lithuania*

INTRODUCTION

At many coastal locations around the world, dunes of various sizes and morphologies have experienced phases of migration in historical times (past 500 years), traversing natural landforms and occasionally entombing entire settlements (Sherman and Nordstrom, 1994; Jimenez *et al.,* 1999; Maia *et al.,* 2005; Pedersen and Clemmensen, 2005; Buynevich *et al.,* 2007a; Forman *et al.,* 2008; Girardi and Davis, 2009; Povilanskas, 2009). With few exceptions, the information on the mode and chronology of dune activity is either limited to general historical accounts or must be reconstructed using a combination of geomorphological, sedimentological, and archaeological techniques. In addition to differences in the length of recorded history, the availability of such important signatures of dune stabilization as soil horizons and dendrochronological records may be limited by a variety of natural conditions. For example, numerous reconstructions of late Holocene and historical dune activity in western and northern Europe have been facilitated by the study of paleosols, ages of extant trees, and relatively long historical archives. In contrast, such databases are extremely limited or absent for most tropical coastal dunefields. Even where present, paleosol ages often bracket dune activity within a broad time interval. Optically-stimulated luminescence (OSL) dates provide direct measurement of the time elapsed since the burial of exposed aeolian strata

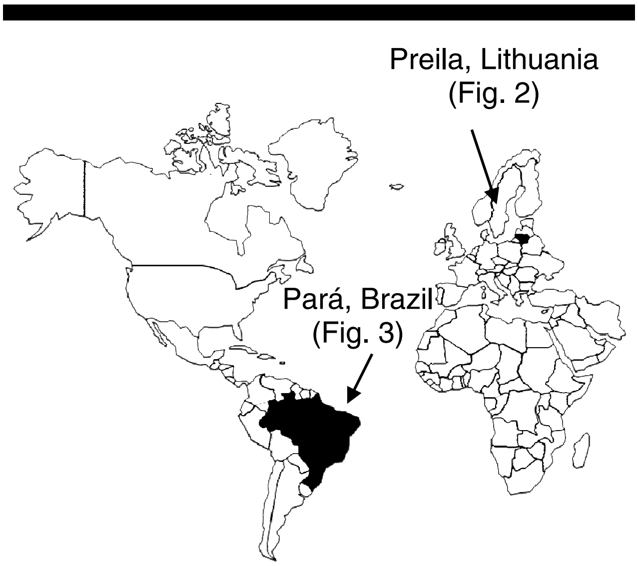

Figure 1. Location of study sites: The Great Dune Ridge, Curonian Spit, Lithuania and Atalaia Beach, Pará, Brazil.

(Clarke *et al.,* 2002). Where high-resolution ground-penetrating radar images are used to identify and map aeolian bounding surfaces, OSL sampling strategy and the ultimate understanding of dune chronology are greatly improved (Bristow *et al.,* 2005; Buynevich *et al.,* 2010). This paper summarizes the preliminary results of OSL dating of the upper slipface strata of large coastal dunes at two sites: 1) Preila, Curonian Spit, Lithuania, and 2) Atalaia Beach, Pará State, Brazil.

PHYSICAL SETTING

Two sites with contrasting physiographic settings were chosen for a comparative study of historical dune migration chronologies. The Curonian Spit is a 100-km-long barrier spit divided between Russian Federation in the south and Lithuania in the north (Figs. 1 and 2A). The study site has some of the highest coastal dunes in northern Europe (>40 m above sea level) and is part of the Great Dune Ridge (Figs. 2A and 2C). Prevailing westerly winds drive the aeolian transport and this landward (eastern) part of the spit is dominated by both active and stabilized Holocene dunes (Gudelis, 1998). The interaction between people and the coastal landscape along the southeast Baltic Sea coast dates back to at least the mid-Holocene, and anthropogenic impact on the landscape became evident during medieval times (12-15th centuries, Gudelis, 1998) and more recent historical period (16-19th centuries). The magnitude and speed of landscape change on local population have reached their peak during the 16-19th centuries (Povilanskas, 2009). During this time, a number of communities were established along the Curonian lagoon seeking protection from the Baltic winds behind the high dunes (Fig. 2B). A part of the temperate forest and one of the villages was buried by the year 1797 by a massive dune (Karvaičiū Kalnas), which is the focus of this study (Fig. 2C).

The second study region is located 240 km east of the Amazon River in coastal Pará State, Brazil (Figs. 1 and 3A). Despite high precipitation rates (>2,000 mm/yr), several large coastal dunes show evidence of continuing activity driven by strong easterly winds (Souza Filho et al., 2009). Two large parabolic dunes (Dune 1 and Dune 2) at Atalaia Beach (Fig. 3) have been actively migrating in the recent past, however the exact chronology of this movement is unknown. This site presents an opportunity to study the style and chronology of the interaction of the dunes with the tropical vegetation and man-made structures.

METHODS

Field observations and measurements of coastal dunes were carried out during October (Brazil) and November (Lithuania) campaigns of 2008. Satellite image analysis was complemented by high-resolution ground-penetrating radar (GPR) images using a digital Geophysical Survey Systems Inc. SIR-2000 GPR system with 200 and 400 MHz monostatic antennas (for technical aspects of GPR and its use in coastal settings, see van Heteren *et al*., 1998; Jol and Bristow, 2003; Buynevich *et al.,* 2009). GPR images were post-processed using RADAN 5.0 software. No topographic correction was applied to sections of profiles that had less than 0.3 m variation in elevation. Geophysical data were groundtruthed using shallow trenches (0.3-1.0 m) and hand augers. Grain size, sorting, organic content, and bulk mineralogy of surficial and subsurface samples were analyzed using standard sedimentological techniques. Optically-stimulated luminescence dates were obtained at the OSL Laboratory, University of Nebraska-Lincoln.

RESULTS

Curonian Spit, Lithuania

A cross-barrier geological transect at Preila served as the basis for establishing dune chronology in this historically active part of the Great Dune Ridge (Fig. 2C). In this wide (> 1km) and high (>40 m) part of the spit, massive aeolian sand transfer, rather than overwash and breaching, has been the dominant process of landward migration since mid-Holocene. GPR images were used to locate key bounding surfaces (superposition and reactivation surfaces) to guide the OSL sampling strategy (Fig. 2D). Three OSL ages are progressively younger in the eastward direction (downwind), as expected: 490±60, 410±60, and 370±50 years before present (present=AD 2009). These dates of the upper sections of buried slipfaces indicate that dune migration of more than 600 m took place between mid-1500s and late 1700s, with rapid advance between AD 1500 and 1630. These ages are consistent with historical records and the time of burial of a coastal village near the edge of a lagoon by the late 1700s.

Equatorial Brazil

At the Atalaia site, northern Brazil (Fig. 3A), two westward-migrating dunes were analyzed using aerial and satellite images, 400 MHz GPR records, and OSL ages of slipface strata. Dune 1 (L=700 m, W=270 m) has a well-developed parabolic shape, exhibits distinct trailing vegetation marks, and is advancing into a mangrove forest (Fig. 3B; Buynevich *et al.,* 2010). The first set of OSL dates suggest recent migration of the dune (from 140±10 to 37±21 years before present; Figs. 3C and 3D). Based on imaged and OSL-dated paleo-dune surfaces, the time-averaged dune migration rate decreased from 1.6 to 1.1 m/yr, with a stabilization of the dune limb approximately 90 years ago. Based on the most recent changes in the position of the dune crest (using geo-referenced2008 ground surveys, 2001 vertical aerial photographs, and 2009 satellite images; Figs. 3B and 3C), Dune 1 continues to migrate at a rate of 1.0 m/yr. Approximately 2,000 m upwind of Dune 1, a rapidly evolving Dune 2 (L=500 m, W=150 m) is migrating into a low-relief residential area (Fig. 2D). Subsurface images indicate that this dune consists of four sedimentary packages (average thickness 4.0 m), which represent distinct phases of dune migration (Fig. 3E). The optical sample taken from the uppermost slipface strata upwind of a partially buried telephone pole gave a nearly modern age (0±34 years). Based on this information, this dune has migrated at an average rate of at least 1.6 m/yr, while accreting vertically at a rate of 0.3 m/yr (Fig. 3E).

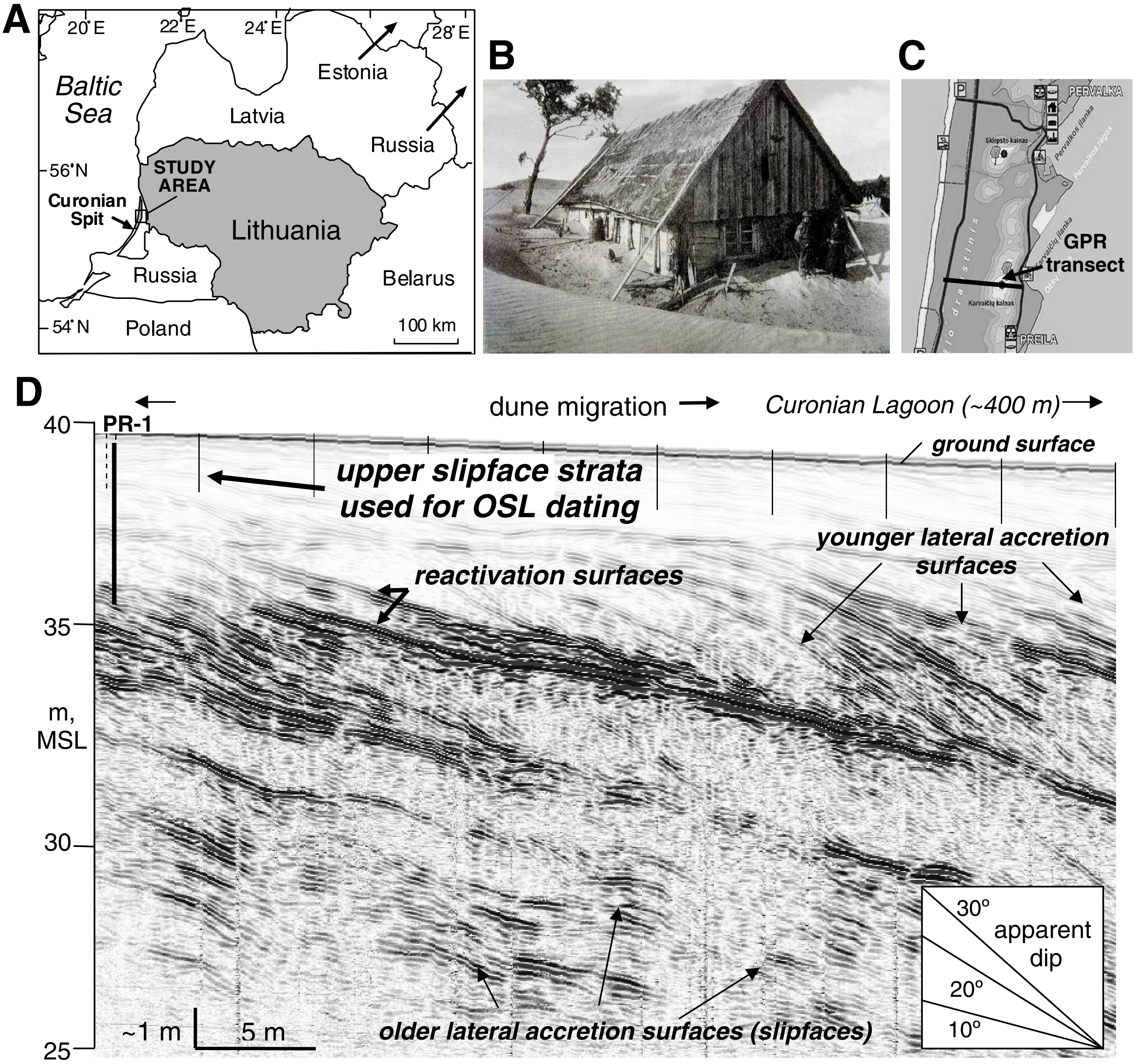

Figure 2. Example of a historically active Karvaičiū dune north of Preila settlement, Curonian Spit, Lithuania: A) Location of the study area; B) a partially buried house along the lagoon shoreline (from Gudelis, 1998); C) Location of the master geophysical profile across the Karvaičiū dune; D) Section of a 200 MHz GPR profile across a recently stabilized dune near Preila (see Fig. 2C for location; PR-1 - hand auger. MSL – mean sea level).

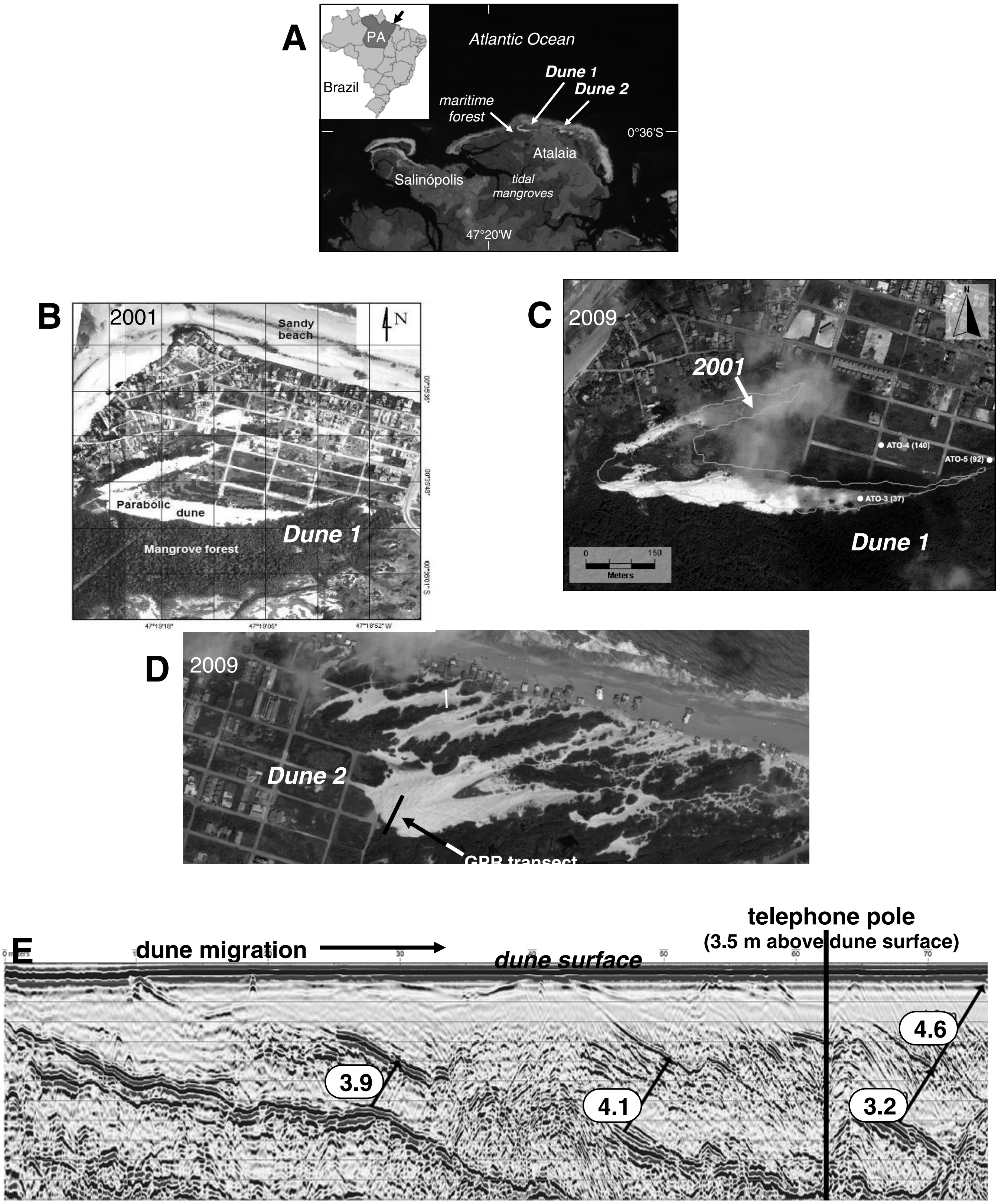

Figure 3. Active parabolic dunes in coastal Pará, Brazil: A) Location of the study area (note the positions of Dunes 1 and 2; GoogleEarth™ image); B) 2001 vertical aerial photograph of Dune 1 showing well-developed vegetation marks between the limbs (arrow); C) 2009 GoogleEarth™ image of Dune 1 with superimposed 2001 outline. Locations of OSL dates (ATO) and median ages (numbers in parentheses) are shown; D) 2009 GoogleEarth™ image of Dune 2, with the location of GPR profile (scale as in Fig. 3C); E) GPR image of Dune 2 showing thicknesses (in meters) of individual aeolian accretionary packages. Note the partially buried telephone pole.

DISCUSSION

The OSL ages indicating a recent migration of the dune at Preila, Lithuania are consistent with historical data for this part of the spit (Gudelis, 1998; Povilanskas, 2009). This chronology contrasts with the nearly 6,000-year migration of the dune at Naglių to the north (Buynevich *et al.,* 2007b), but both sites show reactivation of aeolian processes during the little ice age. The two dunes at Atalaia, Brazil show activity over the past 150 years and were likely migrating prior to that. To the west of the Atalaia site, optical dates indicate that two main coastal dune ridges at Salinópolis (Praia do Maçarico; Fig. 3A) have partially infringed on dense interdunal wetlands and experienced a period of aggradation within the past 80-90 years. To the east, the seawardmost dune generations at Ajuruteua were established in the past 200 years and are backed by relict dunes associated with former shoreline positions dating back to late Holocene (1,000-2,500 years BP). Both recent and future migration patterns and rates of the dunes are affected by downwind topography (tidal channels, vegetation density and height, and intensity of development; Sherman and Nordstrom, 1994; Jimenez *et al.,* 1999; Maia *et al.,* 2005; Buynevich *et al.,* 2007a; Forman *et al.,* 2008; Girardi and Davis, 2009; Buynevich *et al.,* 2010). Our study demonstrates that for a region with limited historical records, integrated morphological and subsurface datasets provide valuable information about the rapidly evolving coastal dunefields. Ongoing research is focusing on integrating the new OSL data with historical records and detailed analysis of reactivation surfaces in GPR records.

CONCLUSIONS

Our geological and chronological data indicate that whereas the two study regions differ markedly in their precipitation patterns, vegetation types, oceanographic setting, and land-use history, both experienced episodes of rapid (average: 1-2 m/year) migration of massive dunes (10-50 m high). This trend continues locally at the present time, although efforts to stabilize the dune with vegetation have been underway along the Curonian Spit for more than a century (Gudelis, 1998; Povilanskas, 2009). Aside from their implications to coastal evolution, accurate reconstructions of dune dynamics on decadal to centennial time scales should be integrated into coastal development and management strategies.

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