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Reactivation of Coastal Dunes Documented by Subsurface Imaging of the Great Dune Ridge, Lithuania

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ABSTRACT

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Large coastal and inland dunefields often consist of multiple generations defined by periods of stability and reactivation. Where earlier phases of aeolian activity are masked by subsequent deposition, continuous high-resolution geophysical images help to reconstruct the history of landscape change. Ground-penetrating radar (GPR) profiles from relict Holocene dunes on the northern Curonian Spit, Lithuania reveal distinct contacts between older deposits (barrier-spit facies, older aeolian strata, paleosols) and overlying dune sands. Early stages of dune migration began prior to 6,000 years B.P. followed by several periods of stabilisation and subsequent reactivation. Parabolic and transverse dunes, some attaining heights of 40-60 m, have migrated to the east in response to westerly winds from the Baltic Sea. In several places, similar to a number of sites in Northern Europe, the upper sections of large dunes have been deflated leaving near-horizontal exposures where subsurface imaging extends the continuity of key stratigraphic horizons. Within dune sequences, oblique lateral accretion surfaces indicate the direction of earlier migration phases and exhibit distinct meso-scale geometries. In GPR images and shallow trenches, buried slipfaces have dip angles varying from 10-15º to 31-34º, the latter being similar to the angle of repose maintained by modern unvegetated dunes. A series of cores taken through sequences of stacked buried slipfaces show little visible variation in sediment properties with depth, suggesting that minor changes in texture, mineralogy and grain packing may be responsible for individual reflections in geophysical records. Occasionally, laterally extensive horizons enriched in heavy minerals produce prominent subsurface reflections and are indicative of periods of increased wind activity.

ADDITIONAL INDEX WORDS: *Curonian Spit, GPR, reflection geometry, truncation, slipface, medieval*

INTRODUCTION

Positioned at the land-ocean interface, coastal dunefields have been active throughout various phases of the Holocene and are sensitive to major reorganisation in the climatic and geological processes along continental margins (BIGARELLA, 1971; HESP and THOM, 1990; CLARKE *et al.*, 2002; CLARKE and RENDELL, 2006). Understanding the effects of environmental and anthropogenic changes on coastal landscapes is particularly important in a current regime of rapid shifts in climate, sea level, and sediment supply, combined with ever increasing population pressures along sandy coasts. One of the fundamental issues regarding the evolution of aeolian landscapes is determining whether a particular dunefield represents a single generation or developed through multiple phases of activity, stability and reactivation.

Many earlier studies of long-term dune dynamics and evolution have been limited to exposures and sediment cores, inability to trench into the older part of the sequence below the water table and challenges in establishing regional correlation of aeolian and intervening organic horizons (BAKKER, JUNGERIUS, and KLIJN, 1990). Recent advances in subsurface imaging technology, such as ground-penetrating radar (GPR), allow rapid collection of continuous records, with decimetre-scale resolution and penetration depths of 5-10 m common for coastal regions (JOL, SMITH, AND MEYERS, 1996; VAN HETEREN *et al.*, 1998; NEAL and ROBERTS, 2000; BUYNEVICH and FITZGERALD, 2001). Even greater penetration (10-30 m) has been obtained in unsaturated dune sands; SCHENK *et al.*, 1993; CLEMMENSEN *et al.,* 2001; VAN DAM *et al.*, 2003; HAVHOLM *et al.,* 2004). GPR allows for rapid imaging of dune stratigraphy, both above and below the water table and provides information on apparent dip angles of lateral accretion and truncation surfaces, paleosol horizons, thickness of aeolian units and relative chronology of dune deposition, migration and deflation (AHLBRANDT and FRYBERGER, 1981; BOTHA *et al.*, 2003; BRISTOW, LANCASTER, and DULLER, 2005).

The Curonian Spit along the southeast coast of the Baltic Sea presents an ideal opportunity to investigate the signatures of reactivation of aeolian activity (Fig. 1). It is located north and east of the sites where dune dynamics and its links to climate change (e.g., storminess and North Atlantic Oscillation regime) have been investigated in recent years (VAN DER MEULEN, 1990; SEPPÄLÄ, M., 1995; KÄYHKÖ *et al.*, 1999; CLEMMENSEN *et al.,* 2001; WILSON *et al.*, 2001; CLARKE *et al.*, 2002).

Figure 1. Location of the study area along the southeast coast of the Baltic Sea. Note the exposure of the Curonian Spit to prevailing westerly winds.

The aim of this paper is to present the first subsurface evidence for dune reactivation along a section of the northern Curonian Spit, Lithuania (Fig. 2) and to compare geophysical signatures of dune migration at two sites along the northern part of the spit. Future chronological control will provide a detailed reconstruction of the Holocene depositional history of this region.

PHYSICAL SETTING

The Curonian Spit, a UNESCO World Heritage Site, is a 100-km-long barrier spit divided between Russian Federation in the south and Lithuania in the north (Fig. 1). It has the highest coastal dunes in northern Europe (more than 60 m above sea level) which are part of the Great Dune Ridge (Fig. 2). With prevailing westerly winds driving the aeolian transport, this landward (eastern) part of the spit is dominated by both active and stabilised Holocene dunes (GUDELIS, 1998). Deflation of relict dunes on the northern part of the spit exposes a number of mappable paleosol horizons with the youngest dating back to the beginning of the Little Ice Age (Fig. 2B; GUDELIS, 1998; BUYNEVICH, BITINAS, and PUPIENIS, 2006.). The geometry and extent of these paleosols allow reconstruction of dune morphology and migration direction similar to some examples of relict dunes along the Polish coast (BORÓWKA, 1975). The earlier, cursory studies in this region suggest that at least four paleosol horizons are regional in extent and that charcoal within paleosols may be related to burning of coastal heathlands as early as 2,000 years ago (MOE, SAVUKYNIENĖ, and STANČIKAITĖ, 2005). The first set of optical dates from several sites place the latest aeolian activity phase at <500 yBP (BITINAS, 2004).

The interaction between people and the coastal landscape along the southeast Baltic Sea coast dates back to at least the mid-Holocene (RIMANTIENĖ, 1999) and the impact on the landscape became evident during medieval times (12-15th centuries A.D.; GUDELIS, 1998). The scale and speed of geological impact on local population have reached their peak during the 15-19th centuries (BUČAS, 2001). During this time, a number of communities were established along the Curonian lagoon seeking protection from the Baltic winds behind the high dunes. Only a few small areas remained forested by the end of 18th century (e.g., Juodkrantė; Fig. 2C). Historical documents suggest that this time was also marked by several mobilisation episodes of large dunefields, triggered largely by land clearance. During this period, a number of Curonian villages were buried by migrating dunes (GUDELIS, 1998; BUČAS, 2001).

METHODS

The internal stratification of Holocene and recent dunes was investigated using high-resolution, continuous ground-penetrating radar imaging (see Fig. 2 for locations of selected segments). We used a digital Geophysical Survey Systems Inc. SIR-2000 GPR system with a 200 MHz monostatic antenna (Fig. 2A; for technical aspects of GPR see VAN HETEREN *et al.*, 1998; NEAL and ROBERTS, 2000; JOL and BRISTOW, 2003; BUYNEVICH and FITZGERALD, 2005). Penetration of up to 10-15 m and resolution of 0.1-0.3 m was typical, depending on the water table depth. The two profile segments chosen as examples were taken along relatively horizontal portions (elevation change <0.5 m) of the vegetated dunes near Preila and Juodkrantė (Fig. 2). A hand-held GPS system provided coordinates for profile locations. At several locations along the GPR lines, geophysical data were ground-truthed using Edelman hand auger.

DUNE REACTIVATION: SUBSURFACE SIGNATURES AND IMPLICATIONS

Recent field investigations and GPR surveys in the area of deflated dunes (Naglių site, Fig. 2B) indicate that reactivation of dune activity is defined by paleosol horizons. This is represented by aeolian sands overlying organic-rich horizons, both having the same dip angle of 31-34°, similar to modern active and vegetated slipfaces. However, in most parts of the spit and in many other dunefields around the world, signatures of dune reactivation are masked by subsequent deposition. Where exposures are lacking or organic-rich horizons have not developed, geophysical surveys provide the only means of assessing the internal architecture of aeolian deposits. Disconformities in dunes may be represented by textural variations or concentrations of heavy minerals (likely related to periods of intensified aeolian activity), which act as key lithological causes of reflections in subsurface profiles.

GPR images from two locations of forested dunes (Fig. 2A, C) reveal clear subsurface signatures of dune reactivation. These are expressed by strong reflections (bounding surfaces) separating the older dune facies below from the sands of the subsequent aeolian phase (Figs. 3 and 4). At the southern site near Preila, the location adjacent to a buried 18th-century village of Karvaičiai, the imaged dune sequence is at least 14-15 m thick (Figs. 2A and 3). A GPR image, which is part of a 2000-m-long cross-barrier transect, shows a series of tangential-oblique reflections (lateral accretion surfaces) below the eastward-dipping buried reactivation surface. They have apparent dip angles of 10-13°, whereas those above are steeper (15-25°), suggesting a minor change in dune migration path following a period of stability. A less-prounced subhorizontal bounding surface truncates the dipping reflections (Fig. 3). Due to approximately W-E profile orientation, the apparent dip of the meso-scale cross-bedding on the images may be considered close to a true dip. A hand auger taken at this site penetrated 4.3 m of unsaturated fine-medium-grained dune sands with no visible heavy-mineral component which suggests that slight textural variations within the cross-stratified aeolian sediments are responsible for the upper third of the imaged sequence.

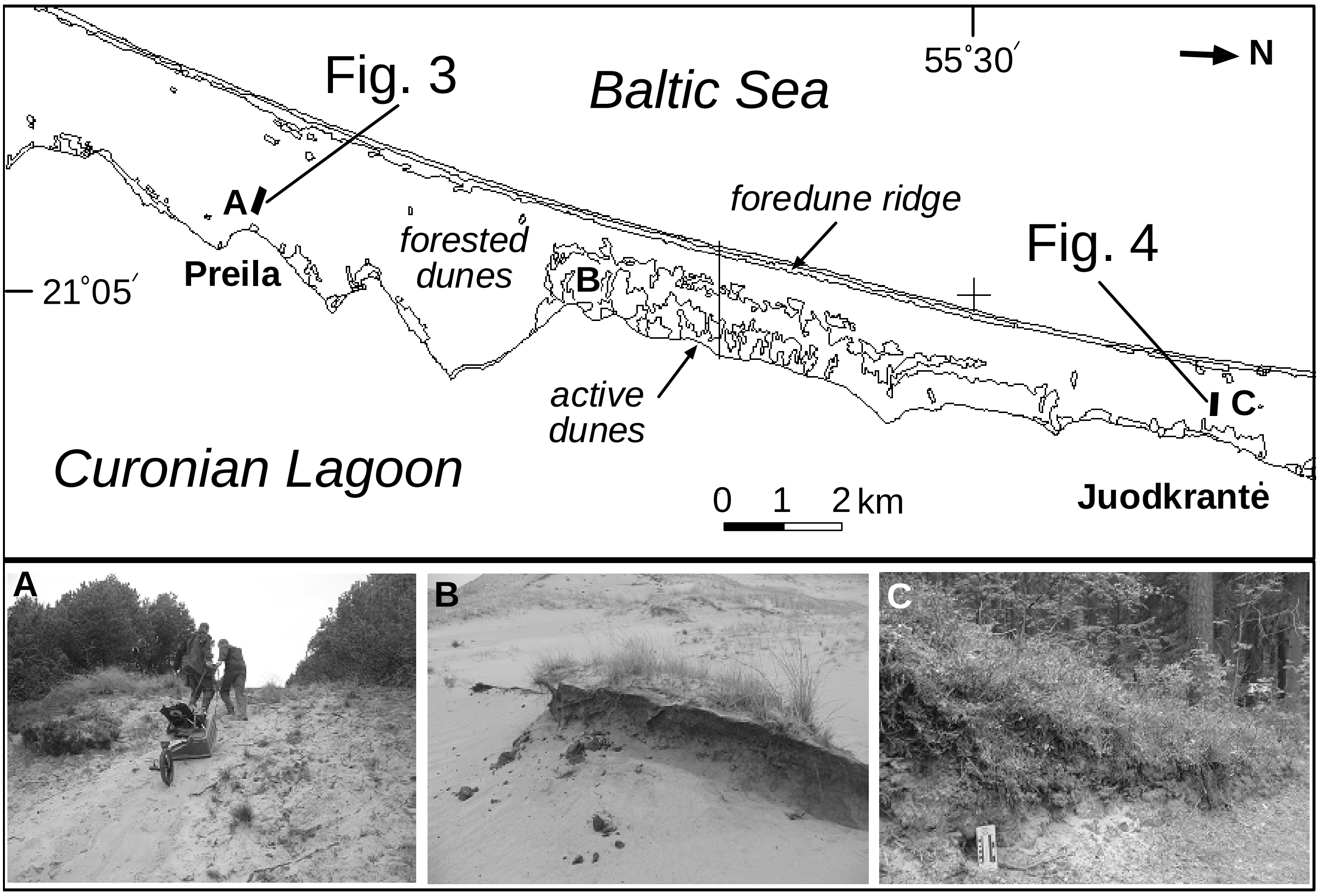

Figure 2. Locations of areas where geophysical surveys demonstrated evidence of dune reactivation. The landward (eastern) part of the spit – the Great Dune Ridge - is dominated by both active and stabilised dunes. Letters A-C refer to field photographs below. A) GPR surveying over the slipface of a recently stabilised dune near Preila; B) paleosols exposed by deflation at Naglių National Reserve; C) Holocene dunes covered by a mature pine forest at Witches Hill, Juodkrantė.

At the northern site of Witches Hill in Juodkrantė, the new phase of dune movement is manifested by substantial changes in dip direction (Figs. 2C and 4). At the bottom of the imaged section, a sub-horizontal hummocky reflection is interpreted as an older stable dune surface. Overlying this surface is an 8-10-m-thick unit of slightly westward-dipping wavy-parallel reflections of an older dune generation. They may represent stoss-side accretion or slipface depositional dip angles near perpendicular to the radar profile. A strong westward-dipping reactivation surface defines the upper contact of these facies. A series of eastward-dipping tangential-oblique reflections above this surface extend for at least 100 m and have apparent dip angles of 20-25º. The change in the direction of dune migration contrasts with the consistent E-SE (downwind) dip seen in Preila profile.

Rapid climatic shifts have been recognised as an important driving force of aeolian system dynamics in both coastal and inland dunefields (VAN DER MEULEN, 1990; LANCASTER, 1997; KÄYHKÖ *et al.*, 1999; CLEMMENSEN *et al.,* 2001; WILSON *et al*., 2001; CLARKE *et al*., 2002). Climate deterioration during the Little Ice Age, likely exacerbated by deforestation, was the likely cause of the latest massive dune migration (WILSON *et al*., 2001; MOE, SAVUKYNIENĖ, and STANČIKAITĖ, 2005). Prior to this period, the regional destabilisation of forested landscapes resulting from natural (lightning) and man-made fires, have been the likely causes of devegetation (FILLON, 1984; SEPPÄLÄ, 1995). Subsurface imaging exemplified here offer a means of rapidly assessing the thickness, geometry and relative chronology of aeolian depositional units. In addition, hyperbolic reflections deep within dune sequences indicate point-source origin (e.g., trees, man-made structures, etc.). Future research efforts will address the role of natural and anthropogenic factors in driving the century-scale landscape dynamics along the SE Baltic Sea coast.

CONCLUSIONS

Geophysical profiles from Holocene dunes on the northern Curonian Spit reveal distinct transitions between aeolian sands of different generations. In some cases, the upper sections of large dunes have been deflated exposing slipface-angle deposition following periods of stabilisation (paleosols). Within 30-40 m-thick dune sequences lacking such exposures, lateral accretion surfaces indicate the direction of sediment transport before and after the stability period or a change in the direction of dune migration. This study emphasises the use of a high-resolution geophysics in assessing the presence and geometry of key lithological boundaries, which can be used to determine the scale and rate of landscape change in coastal dunefields.

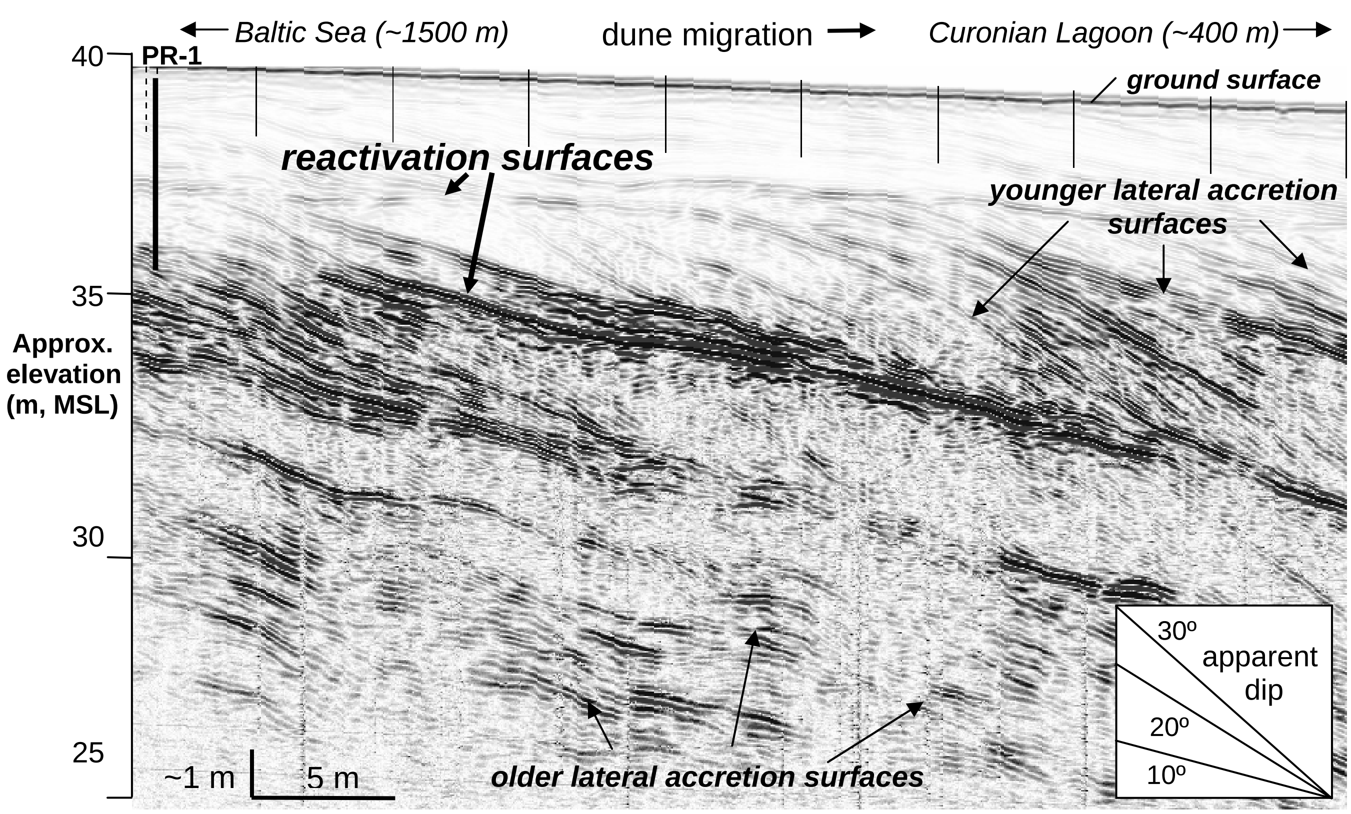

Figure 3. Segment of a cross-barrier GPR profile taken on top of a recently stabilised dune near Preila (see Fig. 2 for location). The range is 200 ns. The location and depth of the auger hole PR-1 is shown at left. MSL – mean sea level.

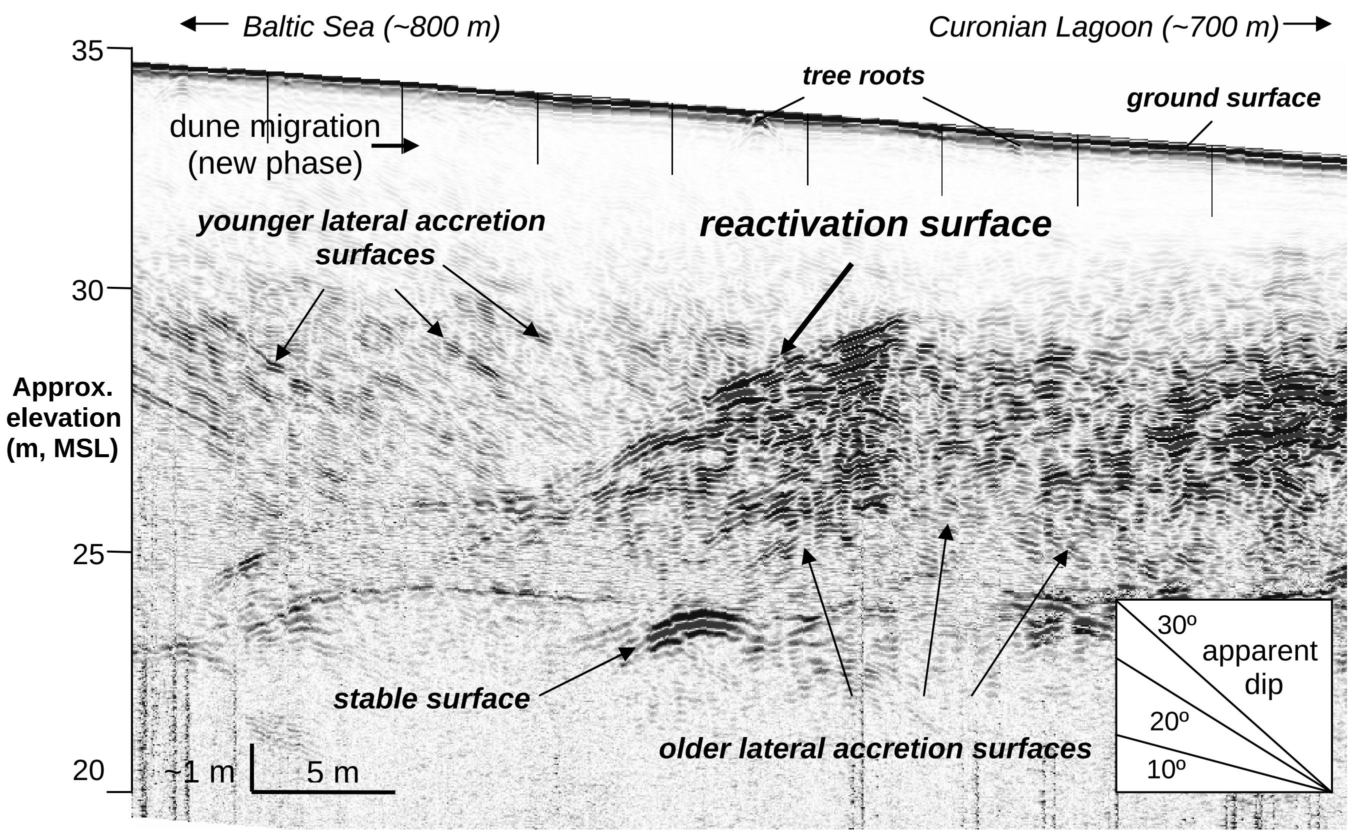

Figure 4. GPR image from forested Holocene dune at Witches Hill, Juodkrantė (see Fig. 2 for location). MSL – mean sea level.

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