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Lithological anomalies in a relict coastal dune: Geophysical and paleoenvironmental markers

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[1] Ground exposures of migration surfaces (slipfaces) of a relict Holocene coastal dune along the southeastern Baltic Sea coast provide an ideal opportunity for establishing the causes of prominent reflections on geophysical profiles. High-amplitude reflections on high-resolution ground-penetrating radar (GPR) images correlate well with two major lithological anomalies: 1) paleosols developed on dune slipfaces, and 2) slipfaces consisting of heavy-mineral concentrations (HMCs). Paleosols serve as indicators of dune stability, represent datable chronostratigraphic surfaces, and help reconstruct dune paleo-morphology. HMCs have substantially higher magnetic susceptibility values than background quartz-rich sands and, where they are well-developed, can be also used for spatial correlation. Based on their occurrence at the study site, these enriched horizons likely represent periods of increased wind activity (storminess). Multiple HMCs upwind of paleosol P1 (800–670 cal years BP) likely reflect periods of intensified wind activity along the southeast Baltic region during the Medieval Warm Period. **Citation:** Buynevich, I. V., A. Bitinas, and D. Pupienis (2007), Lithological anomalies in a relict coastal dune: Geophysical and paleoenvironmental markers, *Geophys. Res. Lett.*, *34*, L09707, doi:10.1029/2007GL029767.

1. Introduction

[2] Coastal dunefields of various sizes and origins are common landforms along many continental margins and are sensitive to major reorganization in the climatic and geological processes [*Hesp and Thom*, 1990; *Lancaster*, 1997; *Wilson et al.*, 2001; *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 [*Carter*, 1991]. In many areas, continuous high-resolution ground-penetrating radar (GPR) images help to reconstruct landscape change, particularly where older periods of aeolian activity are in question [*Clemmensen et al.*, 2001; *Botha et al.*, 2003; *van Dam et al.*, 2003; *Barnhardt et al.*, 2004; *Havholm et al.*, 2004]. Considered some of the most well-sorted sand depositional environments, dune lithosomes may still exhibit dielectrically distinct textural variations resulting from changes in sediment source and wind-flow patterns and intensity. Some sedimentological changes (e.g., grain fabric, packing, grading, and water retention) are sufficient enough to produce distinct signal responses, but may be too subtle to be resolved by standard analyses of sediment cores and outcrops [*van Dam et al.*, 2002]. GPR has been used successfully to identify and map bounding surfaces within dune sequences [*Schenk et al.*, 1993; *Jol et al.*, 1996; *Bristow et al.*, 2005] however few studies have addressed the origin and geological significance of individual reflections [*Guha et al.*, 2005]. The latter is important for accurate correlation of geophysical records with sedimentological features observed in cores or outcrops.

[3] To correlate subsurface reflections with specific sedimentary features, outcrops or trenches are preferable to point-source information from sediment cores [*van Dam et al.*, 2002]. Sequences of preserved dune migration strata (slipfaces) are particularly useful because large numbers of them (each representing a time surface) can be traversed by GPR profiles [*Bristow et al.*, 2005]. Furthermore, areas where thick sequences of slipfaces have been exposed on the ground surface by wind erosion (deflation) provide and ideal opportunity for such an analysis. The nearly horizontal ground exposure helps decrease or avoid the need for topographic correction on geophysical profiles and, more importantly, allows direct correlation of GPR reflections with exposed sedimentary units and their bounding surfaces. Using such an area of a relict coastal dune as an example, we describe the role of the two most prominent lithological anomalies as geophysical marker horizons. We then discuss their importance for geomorphological and paleoenvironmental reconstruction of coastal dune landscapes.

2. Study Area

[4] The field site suitable for correlation of subsurface records with extensive ground exposures of dune migration sequences is located on top of a deflation surface of a relict Holocene dune in the Naglių Nature Reserve, Lithuania (Figure 1). This site is situated 25 m above mean sea-level on the landward (eastern) flank of the Curonian Spit, a 97 km-long barrier spit stretching in a SW–NE orientation along the southeast Baltic Sea coast. The spit is a UNESCO World Heritage Site divided between Russian Federation in the south and the Republic of Lithuania in the north (Figure 1a). It has the highest coastal dunes in northern Europe (more than 60 m above sea level) which form the Great Dune Ridge (Figure 1b). With prevailing westerly winds driving the aeolian transport, the landward eastern part of the spit is dominated by both active and stabilized Holocene dunes (Figure 1b) [*Gudelis*, 1998; *Žilinskas et al.*, 2001; *Bitinas*, 2004]. Deflation of relict dunes on the northern part of the spit exposes a number of regionally

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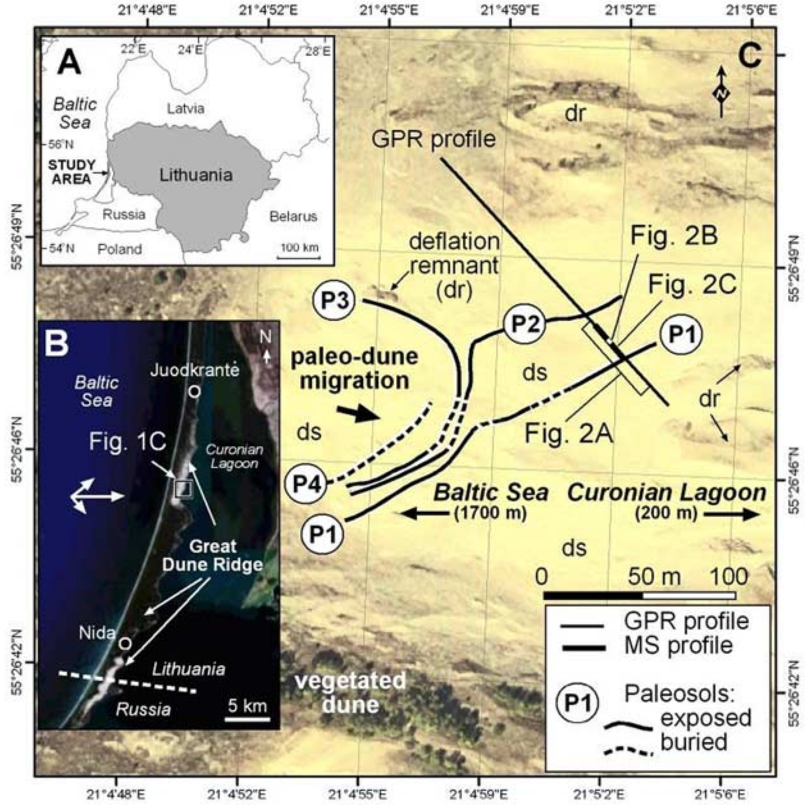

Figure 1. (a) Location of the Curonian Spit along the southeast coast of the Baltic Sea. The study area is in the northern part of the spit, Lithuania. (b) Location map of the Naglių study site along the Great Dune Ridge. Arrows at left show directions and relative magnitudes of prevailing winds responsible for aeolian sediment transport (wind directions after *Žilinskas et al.* [2001]). (c) Vertical aerial photograph of the Naglių site showing the distribution of deflation surfaces (ds) and deflation remnants (dr), geometry and extent of paleosols (based on exposures and subsurface data), as well as locations of a GPR profile, magnetic susceptibility (MS) transect, and a shallow trench.

correlative paleosol horizons (Figures 1c) [*Gudelis*, 1998]. Historical documents indicate that massive dune reactivation episodes during the 1600–1800s were triggered largely by land clearance, which coincided with climatic deterioration during the Little Ice Age and resulted in sand invasion and burial of several coastal villages [*Bučas*, 2001; *Moe et al.*, 2005].

3. Methods

[5] The present study of sedimentological causes of GPR reflections was based on ground exposures and geophysical records of unsaturated portions of the dune sequence. The outcrops of paleosols and visible sedimentological changes within dune sands (e.g., textural variations, heavy-mineral concentrations (HMCs), etc.) were mapped in the field using a compass and hand-held GPS. The internal stratification was investigated using a grid of intersecting ground-penetrating radar profiles with 40–50 m spacing (for clarity, only one profile is shown in Figure 1c). We used a digital Geophysical Survey Systems Inc. SIR-2000 GPR system with a 200 MHz monostatic antenna (for technical aspects of GPR see *Jol and Bristow* [2003], *van Heteren et al.* [1998], and *Buynevich and FitzGerald* [2005]). Penetration of up to 20 m and resolution of 16–18 cm was typical for unsaturated dune sands. GPR image post-processing with RADAN 5.0 software included a linear gain increase to accentuate major subsurface reflections. Geophysical data were ground truthed using shallow trenches (0.3–1.0 m) and sediment cores (2–5 m) were collected at key locations on GPR profiles using Edelman hand auger. Depths of excavated dipping paleosol horizons were used to calculate the electromagnetic wave velocity of 13 cm/ns for unsaturated dune sands. Grain size, sorting, organic content, and bulk mineralogy of surficial and subsurface samples were analyzed using standard sedimentological techniques.

[6] For documenting lithological differences between exposed heavy-mineral concentrations and background quartz-rich sands, magnetic susceptibility (MS) measurements were taken in-situ along a surface profile using Bartington MS2K field scanning sensor (relative sensitivity decreases to 50% at surface diameter of 2.5 cm and the depth of 0.3 cm). Due to this response decay with depth, the field sensor is ideal for measuring relative MS values on moderately smooth sediment surfaces, particularly where sampling of thin HMC horizons is problematic. The 20-m-long MS profile was collected westward (upwind) of paleosol P1 along a portion of the GPR profile, with measurement of every visually expressed HMC and intervening quartz-rich sands (Figure 1c). A 0.4-m-deep trench excavated on the profile was used to confirm the subsurface extent of the HMCs and obtain detailed MS measurements

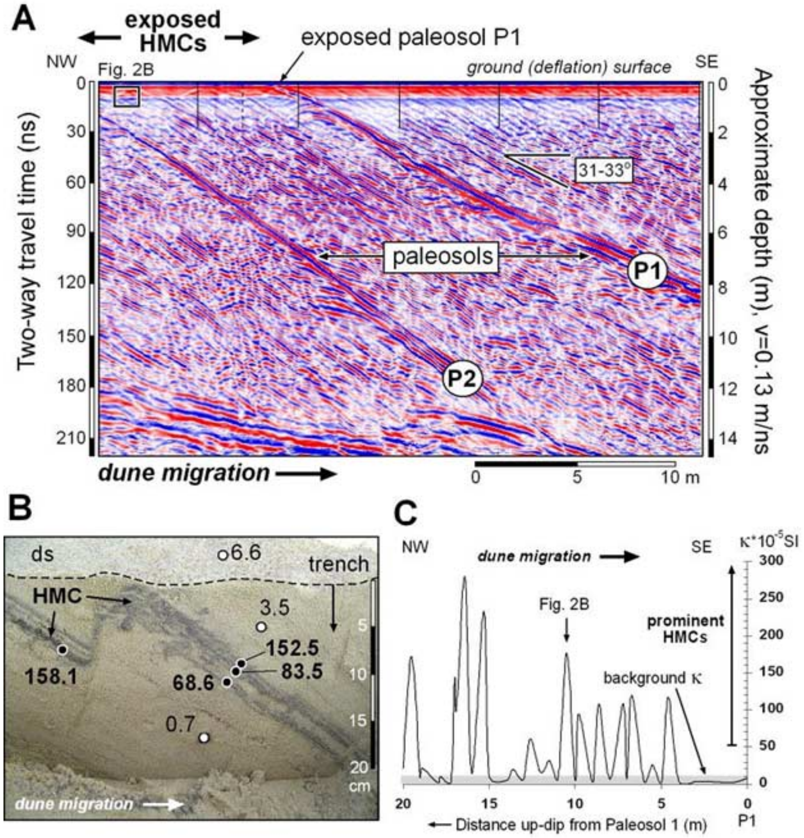

Figure 2. (a) Ground-penetrating radar transect across the younger part of the relic dune (see Figure 1c for profile location). Paleosols P1 and P2 are clearly visible. The numerous prominent reflections in the surrounding aeolian sands coincide with heavy-mineral concentrations (HMCs) exposed on the deflation surface and confirmed in trenches and sediment cores. (b) Photograph of a trench excavated on the GPR/MS profile 10.5 m upwind of paleosol P1 (ds – deflation surface; see Figures 1c and 2a for trench location). (c) In-situ volume magnetic susceptibility values (dimensionless κ, *10–5 SI) along a profile extending 20 m upwind of paleosol P1. There is a clear contrast between HMCs ($\kappa > 50$) and background quartz-rich sands ($\kappa < 10$). Note the absence of HMCs within 4 m of P1 (aeolian sands deposited prior to paleosol formation).

(Figure 1c). Samples of charcoal from paleosols P1 and P2 were dated by AMS technique at the National Ocean Sciences Accelerator Mass Spectrometry facility at the Woods Hole Oceanographic Institution.

4. Results

[7] The exposures of paleosols, complemented with GPR profiles and sediment cores, allow reconstruction of their geometry and extent within a relict dune sequence (Figure 1c). At least four 10-40 cm-thick paleosols are clearly visible in geophysical records and constitute the most prominent reflections (Figure 2a). Based on measurements in trenches and cores, the true dip angle of these organic-rich layers is 31–33°, which mimics the angle-of-repose gradient of the large-scale cross-bedding (buried dune slipfaces). The azimuth of the true dip ranges between east and southeast, consistent with the prevailing wind direction (Figures 1b and 1c). Charcoal samples from paleosols P1 and P2 yielded dates of 850 ± 35 and 1,350 ± 45 ^{14}C years BP (2σ), respectively, which were OxCal-calibrated to 800–670 and 1,340–1,170 cal years BP. These dates bracket the age for the intervening aeolian sequence.

[8] The grain size of the quartz-rich aeolian sediments varies only slightly within the relict dune sequence (mostly in the medium sand range), with heavy minerals (primarily magnetite and almandine garnet) commonly comprising the finer fraction due to their higher density. A number of individual cross-beds consist of lithological anomalies - heavy-mineral concentrations (HMCs), which are exposed on the deflation surface. They vary between 1 and 8 cm in thickness and coincide with the most prominent (high-amplitude) subsurface reflections, thereby greatly accentuating the electromagnetic GPR signal response (Figure 2a). HMCs typically have more than 30% heavy mineral fraction (primarily magnetite, garnet, and epidote), in contrast to less than 5% in the background aeolian sands (Figure 2b). The in-situ volume magnetic susceptibility (MS) measurements of heavy-mineral horizons and enclosing quartz-rich sands, taken both in shallow trenches and along a surface profile, demonstrate clear distinction between these two lithologies. Because magnetic susceptibility is primarily a function of magnetite content [*Shankar et al.*, 1996]. HMCs have substantially higher susceptibility values. Values of $\kappa > 50$ (dimensionless, *10^{-5} SI), with the most enriched horizons exhibiting $\kappa > 100$, contrast with those of background

quartz-rich sands ($\kappa < 10$; Figures 2b and 2c). Therefore, the MS values can be used as a proxy for enrichment of heavy minerals within a dune sequence. As stated above, the volume MS values measured in the field are substantially lower than mass-specific MS due to response decay within the outer 1 cm.

5. Discussion and Conclusions

[9] The results of geophysical and sedimentological investigation demonstrate the importance of paleosols and heavy-mineral concentrations as both geophysical and paleoenvironmental markers. The high-amplitude GPR signal response to paleosols is the result of both their thickness and lithological (textural and compositional) contrast with enclosing aeolian sands [*van Dam et al.*, 2002; *Botha et al.*, 2003]. The paleosols, therefore, produce excellent subsurface reflections which can be traced spatially and to a depth of at least 12–14 m below the ground surface (Figures 1c and 2a). In the study of coastal dunefields, paleosols of various extent and thickness have long been used as indicators of landscape stability [*Borówka*, 1975; *Sevink*, 1991; *Pye*, 1993; *Wilson et al.*, 2001; *van Dam et al.*, 2003; *Havholm et al.*, 2004; *Clarke and Rendell*, 2006]. The four paleosols (P1–P4) mapped at Naglių suggest periods of dune stability separated by episodes of aeolian activity. The positions, geometry, and dip angles (31–33°) of paleosols indicate that vegetation periodically covered the successive slipfaces of a relict dune, similar to large parts of modern stabilized dunes along the Great Dune Ridge (Figure 1b). *Pye* [1993] described similar mode of preservation of organic-rich horizons in Australian coastal megadunes. Presence of charcoal in three younger paleosols at Naglių (P1–P3) suggests forest or brush fire activity [*Fillon*, 1984; *Seppälä*, 1995; *Moe et al.*, 2005].

[10] Due to their relatively rapid development in temperate dune regions [*Sevink*, 1991] and high organic content, paleosols also represent chronostratigraphic references [*Borówka*, 1975; *Wilson et al.*, 2001; *Clarke et al.*, 2002; *Havholm et al.*, 2004]. The age of 800–670 cal years BP for paleosol P1 suggests a period of relative stability and establishment of vegetation on the dune prior to the inception of the Little Ice Age in Europe [*Clemmensen et al.*, 2001; *Wilson et al.*, 2001]. Based on bracketing ages, the dune sequence between paleosols P1 and P2 represents deposition during the Medieval Warm Period (1200–800 cal yBP) [*Klijn*, 1990; *Wilson et al.*, 2001; *Sridhar et al.*, 2006]. In addition to serving as paleoenvironmental indicators and chronostratigraphic markers, the geometry and extent of paleosols often allow reconstruction of dune morphology and migration patterns. For example, using dip angles of paleosols exposed along the Polish coast, *Borówka* [1975] was able to reconstruct the height and plan shape of a relict dune. Paleosols at Naglių site indicate that the initial parabolic dune morphology with an easterly migration path (paleosols P3 and P4) subsequently changed to a transverse dune with a south-easterly migration path (paleosols P1 and P2; Figures 1c and 2a).

[11] In some regions, especially where paleosols may be absent, well-developed heavy-mineral concentrations can be used as marker horizons for spatial correlation of dune facies and for reconstruction of dune morphologies. Because of their dielectric properties, heavy minerals produce high-amplitude reflections in GPR profiles, especially where thicker HMCs are comparable to vertical resolution of the electromagnetic georadar signal (8–10 cm) [*Guha et al.*, 2005]. The sharp contrast in magnetite content of background sands and the HMCs is confirmed by the in-situ volume magnetic susceptibility values, which are 10–15 times higher for enriched horizons (Figure 2c).

[12] In addition to their use as sedimentological and geophysical marker horizons, heavy-mineral concentrations can be used as proxies for sediment transport conditions. Just as HMCs are diagnostic of storm erosion in beach sediments [*Komar and Wang*, 1984; *Buynevich et al.*, 2007], in dunes sands they are likely related to substantial increases in wind velocity causing preferential winnowing and/or prolonged suspension transport of light minerals (quartz and feldspar) [*Bagnold*, 1954; *Sauermann et al.*, 2003]. This, in turn, results in an increase in the proportion of denser minerals (garnet, magnetite, ilmenite, epidote, zircon, hornblende, etc.) in a given grain-size fraction [*Masui*, 1952; *Kattaa*, 2004]. Because the study site is located far away from heavy mineral sources (both glacial deposits and the nearshore zone), most enrichment likely occurred by progressive deflation within the Great Dune Ridge. For example, periods of increased wind activity (storminess) are expected to produce higher number or degree of concentration of HMCs in an aeolian depositional sequence. Also, the absence of HMCs immediately upwind of paleosol P1 (0–4 m; Figure 2c) may represent a relatively calm period preceding dune stabilization, although the rate of aeolian deposition for such a short part of the sequence is difficult to ascertain.

[13] The HMCs predating paleosol P1 are likely the result of episodes of intensified aeolian activity during the Medieval Warm Period, although HMCs occur in other parts of the sequence as well (e.g., upwind of P1; Figure 2a). The present study illustrates the potential use of HMCs as proxies for the intensity of aeolian sediment transport. Ultimately, the quantitative approach of using aeolian sediment properties to reconstruct paleo-wind intensities will provide valuable information on centennial-to-millennial scale climatic variability in the southeast Baltic region and can be extended to other coastal and continental dunefields.

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