ABSTRACT

Future changes in climate and sea level are likely to increase the threat from storm surges in many coastal regions. Mitigation of this threat requires an understanding of storm surge magnitude and frequency, and the relationship of these variables to climate parameters. This understanding is currently limited by the brevity of instrumental records, which rarely predate the twentieth century. However, evidence of former storm surges can be recorded in coastal dunes, because the dune topography may trap high-magnitude deposits at elevated locations. Here we combine a range of techniques to extract storm-surge data from coastal dune sediment. The sediment is tracked in the subsurface with ground-penetrating radar (e.g., stimulable luminescence [OSL] methods, combined with Monte Carlo simulations of radiation deposition. Finally, the interpretation of the deposit is validated against eighteenth century documentary sources.

SEDIMENTOLOGY

For this research we described and analyzed storm-surge sediment temporarily exposed within a 1-km-long stretch of coastal dunes near Heemskerk, Netherlands (Fig. 1). This dramatic exposure was created during a significant storm surge in November 2007, which eroded the foredune back by 10–15 m at the field location. The striking feature of this exposure was a discontinuous, convolute bed of shell-bearing sand, 10–15 cm thick. The shell unit undulated in height along the exposure, commonly exceeding 4 m +NAP (NAP, the national vertical datum in the Netherlands, is roughly mean sea level), and in some places dipping below the dune foot (~2.5 m +NAP). The exposed shell unit reached the highest point of 6.5 m +NAP at section HK-1, where it was observed as a series of convex-side-up shell layers separated by sand beds. Locally, the unit was observed to truncate the underlying dune sand (HK-V, HK-VII; see Fig. 1).

The mass of the shells, found with scattered pieces of brick and intact bivalves, rules out eolian transport. Moreover, the convolute beds and other deformation structures of the shell unit are indicative of near-surface saturation by water during formation: air, trapped by a water-saturated upper zone and compressed by pressure from the water column, deforms the surrounding sediment (De Boer, 1979). As the maximum elevation of the shell unit far exceeds normal water levels (mean high water is ~0.9 m +NAP), the extensive shell layers would open a new avenue of research on former storm surge conditions.

The shell layers consist mainly of fossil molluscs reworked from Holocene shoreface and tidal-channel deposits. Mollusc composition differs little from that of present-day Dutch beaches, with the presence of mollusc species typical of water shallower than ~15 m ~NAP (e.g., Cerastoderma edule, Macoma balitica, Angulus fabulus, A. tenuis), as well as species...
typical of deeper water (e.g., Spisula subtruncata, Macrura corallina, Donax vittatus, and the gastropod Euspira pulchella). The only double-valved specimens found in the storm surge unit were Cerastoderma edule; ~50 of these were clustered at section HK-IV. As there was no sand inside any of these specimens, it is likely that they were alive when they were uprooted from the seabed and washed onto shore at the time of the storm surge.

Information on the inland extent of the shell-rich unit was obtained through ground-penetrating radar (GPR). The exposed bluff face at section HK-VI provided an ideal starting point for GPR profiling, allowing immediate ground-truthing of the GPR signatures (Fig. 2). The shell unit is identifiable as a planar, high-amplitude reflection that shows a gentle overall dip in a landward direction. The continuous reflection extends to 1 km inland, where it appears to be linked to former interdune lows. At these inland locations, wind-blown pits, bored holes, and hand-dug trenches provided further verification of the GPR signature.

The distribution of the storm surge unit reflects a contemporary frontal dune configuration that differs from the artificially maintained sand dune marking the modern coastline. In historical times, vulnerable lows in the dune ridge were not uncommon, as testified by numerous paintings and drawings. Several dune gaps were present near Heemskerk during the eighteenth century (Kops, 1798). The presence of these gaps explains the nature and lateral distribution of the observed storm surge unit. Water entered the inner dunes through gaps, scouring wide channels, overtopping low dunes, and depositing extensive perched fans (cf. Morton and Sallenger, 2003) and sheets. Sand and shells were transported landward and deposited mainly behind the frontal dunes and other large obstacles, where current velocities and wave energy diminished. The fact that the exposed shell layers were overlain by thick units of eolian sand is the result of steady coastal erosion since their deposition, and an associated landward shift of the frontal dune. Annual coastal profiles from the research area show that the dune crest and dune foot have shifted landward by 30–40 m since A.D. 1965. Before that time, the frontal dune was located even farther seaward, placing the initial storm-surge unit behind the ridge and therefore not buried, or only slightly buried, for part of its existence.

**DATING**

OSL dating was conducted on three sections of the frontal dune (HK-I, HK-III, and HK-VII), plus one section 600 m inland (ZN-I) that had previously been studied in a former exposure, but had not been reliably dated (Jelgersma et al., 1995). The OSL signal of quartz grains is reset by daylight exposure during transport of the grains, and builds up after burial through absorption of naturally occurring ionizing radiation. By using grains of quartz embedded in the sediment, OSL provides a direct means of dating an event, often when no other dating method is suitable. However, the OSL dating of flood deposits provides two significant challenges. (1) The exposure of quartz grains to sunlight during the event may be insufficient to completely reset the OSL signal, leading to an overestimate of the age. However, using recent developments in signal processing (Cunningham and Wallinga, 2010), this effect was found to be insignificant for all but one sample (for methods, see the GSA Data Repository1; also see Figs. DR1–DR3 and Tables DR1–DR2 therein). (2) A more serious challenge is the heterogeneous nature of

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1GSA Data Repository item 2011311, methods, Figures DR1–DR6, and Tables DR1–DR4, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
flood sediments. For several of the storm surge samples, a high proportion of marine shells (~30% by weight) prohibits the usual approach to estimating the ambient radiation dose rate, as the shells have a significantly different radionuclide concentration from that of the surrounding sediment. To overcome this difficulty, we constructed a model of the deposition of beta electrons in the sediment, using a Monte Carlo transport code (Briesmeister, 2000; Schart et al., 2002; Nathan et al., 2003), and determined the correction that should be made to the dose-rate calculations. With these techniques (detailed in the DR methods and Figs. DR4–DR6 in the Data Repository) we found consistent ages for the storm surge samples, validated by high-precision OSL ages on the overlying and underlying eolian sediment.

The OSL ages (Fig. 3; Table DR3) obtained for the three frontal dune sections indicate similar patterns of deposition across the three sites, categorized as follows: (1) eolian deposition prior to the storm surge event, A.D. 1600–1750; (2) deposition and deformation of sediment associated with the storm surge, A.D. 1760–1785; (3) eolian deposition following the storm surge event, A.D. 1775–1900. All three sections show an age gap between phases 1 and 2, most likely caused by erosion of material during the storm surge (apparent from the sedimentology). The inland section shows a similarly phased chronology, except that the underlying dune sand (A.D. 1100) was deposited during an earlier period of eolian activity when the coastline was much farther seaward than today (Hallevaas, 1981). For this site, the apparent age gap between phases 1 and 2 is more likely due to a hiatus in deposition.

**DISCUSSION AND CONCLUSION**

The existence of a significant storm surge in the late eighteenth century is confirmed by contemporary documentary sources. While reliable observations of surge height were not recorded at the time, written accounts attest to two major events taking place within the period determined by the OSL dating. These events occurred in consecutive years, 1775 and 1776 (Hering, 1776, 1778). Although there are no records concerning the field site, there are fragmentary records of the impact these storm surges had on more populated areas of the western Netherlands; these mostly concern the 1775 event. At the coastal town of Scheveningen, ~45 km south of the exposure site, half the town was flooded. Eyewitness accounts from Petten (20 km north of the site) recount the cutting of incipient channels into the frontal dune (Anonymous, 1776).

The extraction of sedimentary storm-surge records has hitherto exploited back-barrier sediment, notably hurricane overwash deposits in the western Atlantic (Donnelly et al., 2004; Boldt et al., 2010). Such records can determine storm surge frequency during the late Holocene, and are particularly useful when they can be linked to climate parameters (Donnelly and Woodruff, 2007; Mann et al., 2009). The nonuniform topography of barrier systems makes analysis of their sedimentary record more challenging; nevertheless, an understanding of the subsurface can be gained through GPR profiling. The erosional signatures of storm surges have previously been identified in radar profiles (Bristow et al., 2000; Buynevich et al., 2004; Switzer et al., 2006). Furthermore, Buynevich et al. (2007) were able to use buried erosional scarps in a prograding barrier as a record of storm-surge frequency, with age constraints provided by OSL dating of the overlying sediment. Our methodology offers a new dimension in flood risk analysis. First, the elevation of the deposits within the dunes can be used to infer magnitude of storm surges, information that is not recorded in back-barrier sediment or erosional features. Second, the dune environment enables the use of OSL to date the sediment with a high degree of precision. The
importance of the dating should not be underestimated, as precise dating in the Little Ice Age period is particularly difficult by other methods. This study further extends the use of OSL to shell-rich sediments, or other sediments with heterogeneity on the millimeter scale. Given the ubiquity of coastal dune systems, and the potential information on Little Ice Age storm surges contained within, this methodology could prove a vital tool in flood risk prediction under a changing climate.

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