

Episodes of aeolian sand movement on a large spit system (Skagen Odde, Denmark) and North Atlantic storminess during the Little Ice Age

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Late Holocene coastal dune successions in north-western Europe contain evidence of episodic aeolian sand movement in the recent past. If previous periods of increased sand movement can be dated sufficiently precisely and placed in a correct cultural and geomorphological context, they may add to our understanding of storminess variation and climate change in the North Atlantic during the later part of the Holocene. In this study, coastal cliff sections of Holocene dune sand were investigated in the north-western part of the Skagen Odde spit system in northern Denmark. Four units of aeolian sand were recognized. Optically stimulated luminescence (OSL) dating indicates that aeolian sand movement took place in four phases: around AD 1460, between AD 1730 and 1780, around AD 1870, and since about AD 1935. The first phase of sand movement occurred during cooling in the first part of the Little Ice Age. A change in the atmospheric circulation, so that both the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) were negative, apparently led to an increased number of intense cyclones causing inland sand movement and dune building. The second and third phase of aeolian sand movement during the Little Ice Age also took place in periods of increased storminess, but during these events it appears that negative NAO values were coupled with positive AMO values. The final phase of sand movement is intimately linked to the modern formation of frontal dunes which takes place during moderate storminess. These findings are important as they indicate three major periods of aeolian sand movement and storminess during the Little Ice Age.

Keywords: Aeolian sand movement, storminess, climate change, Little Ice Age, Skagen Odde.

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Coastal dunefields in north-western Europe have experienced episodic activation throughout the later part of the Holocene (e.g. Clarke & Rendell 2009, 2011; Clemmensen *et al.* 2009). If dated sufficiently precisely and placed correctly in a cultural framework, periods of aeolian sand movement within the dunefields may act as proxy records of past wind climate and North Atlantic storminess variation (e.g. Clemmensen *et al.* 2001a; Clemmensen *et al.* 2007; Madsen *et al.* 2007; Clarke & Rendell 2009; Clemmensen *et al.* 2009).

Numerous studies (e.g. Pye & Neal 1993; Knight *et al.* 1998; Wilson *et al.* 2001, 2004; Clarke *et al.* 2002; Clarke & Rendell 2009; Clemmensen *et al.* 2009;

Reimann *et al.* 2011) report extensive aeolian sand movement and transgressive dune formation along north-western European shores during the Little Ice Age (LIA) between approximately AD 1350 and AD 1900 (Hass 1996). This phase of large-scale aeolian sand movement has been related to increased North Atlantic storminess (e.g. Clarke & Rendell 2009; Clemmensen *et al.* 2009). Aeolian sand invasion was particularly severe along the Danish west coast of Jutland where transgressive dunes formed by persistent westerly storm winds migrated up to 10 km inland during this period (Clemmensen *et al.* 2007; Clemmensen *et al.* 2009). Also the Skagen Odde spit system in north-

ernmost Denmark (Fig. 1) saw extensive inland sand movement in this period, and the northernmost part of the spit landscape became almost completely covered by aeolian dunes and sand plains (Clemmensen & Murray 2006). The majority of these transgressive (parabolic) dunes are now stabilized by vegetation (Anthonsen *et al.* 1996; Clemmensen & Murray 2006; Clemmensen *et al.* 2014).



Fig. 1. Location map. The study area is situated at the north-western side of the Skagen Odde spit system (see Fig. 2). Locations of Rønbjerg Mile (RM) and Rubjerg Knude (RK) are given.

On Skagen Odde and in nearby areas along the west coast of Jutland, the termination of sand movement and transgressive dune formation during the LIA is relatively well dated to the end of the 19th century (Clemmensen & Murray 2006). However, the initiation and early history of this event is poorly dated. This is primarily thought to reflect that the first sand deposited during this event was frequently reworked during later periods of sand movement, so that material available for dating of the initiation of the event therefore is missing at most places (Clemmensen & Murray 2006). Aeolian sediments deposited during the LIA are exposed in coastal cliffs south of Højen on the north-western side of the Skagen Odde spit (Fig. 2). Due to coastal retreat the aeolian sediments represent wind-blown sand originally deposited up to 1300 m inland.

The purpose of this study is to investigate these exposures, to document the sedimentary characteristics of the aeolian sand, and to use optically stimulated

luminescence (OSL) dating to obtain ages of the initiation and later phases of the LIA sand invasion on Skagen Odde. The OSL ages presented in this study are discussed in relation to human impact on the dune environment (e.g. Brüel 1918; Jessen 1936; Hansen 1964; Hauerbach 1992), historical records of sand invasion (Brüel 1918; Clemmensen & Murray 2006), observational and instrumental records of wind climate (Anthonsen *et al.* 1996; Clemmensen *et al.* 2014), and theoretical considerations on North Atlantic storminess during the LIA (e.g. Raible *et al.* 2007, 2008; Trouet *et al.* 2009; Trouet *et al.* 2012; Van Vliet-Lanoë *et al.* 2014). Data extracted from the sedimentary characteristics of the coastal dune succession at Skagen Odde, together with new age control of the aeolian activity phases, allow us to discuss the conditions that led to increased storminess and widespread aeolian sand movement in large parts of north-western Europe during the LIA.

Study area

Skagen Odde (northern Jutland, Denmark) is one of the largest spit systems in Europe. The spit, which now has a length of more than 30 km, developed over the past 7000 years and spit growth towards the north-east is linked to a relatively continuous supply of marine sand and gravel transported north-eastward by longshore currents (Petersen 1991; Hauerbach 1992; Clemmensen *et al.* 2001b; Nielsen & Johannessen 2008). Skagen Odde lies between the waters of Skagerrak (high-energy wave climate) and Kattegat (less high-energy wave climate) (Fig. 1). The spit experiences uplift due to isostatic rebound with present values around 1.5 mm/year (Clemmensen *et al.* 2001b). The western part of the spit from Højen and southwards (Fig. 2) is retreating and nice exposures of the spit deposits are frequently seen, especially after storm and wave erosion of the cliffs, or after strong winds.

The spit deposits are composed of a lowermost marine succession overlain by swale peat (martør) and an uppermost succession of aeolian deposits (Clemmensen *et al.* 2001b; Clemmensen & Murray 2010). For this study, four closely situated sites immediately north of Pælebakke Klit 300–1000 m south of Højen on the north-western side of the spit were selected (Fig. 2). Frontal dunes reaching heights up to 20 m above sea level have developed; the frontal dunes are separated by large wind gaps leading inland to dome-shaped dunes or incipient parabolic dunes. Wind gaps and related dome-shaped dunes reach up to about 300 m inland. At the study area the exposed part of the marine spit succession is relatively thin and composed of upper shoreface and beach conglomerates typically

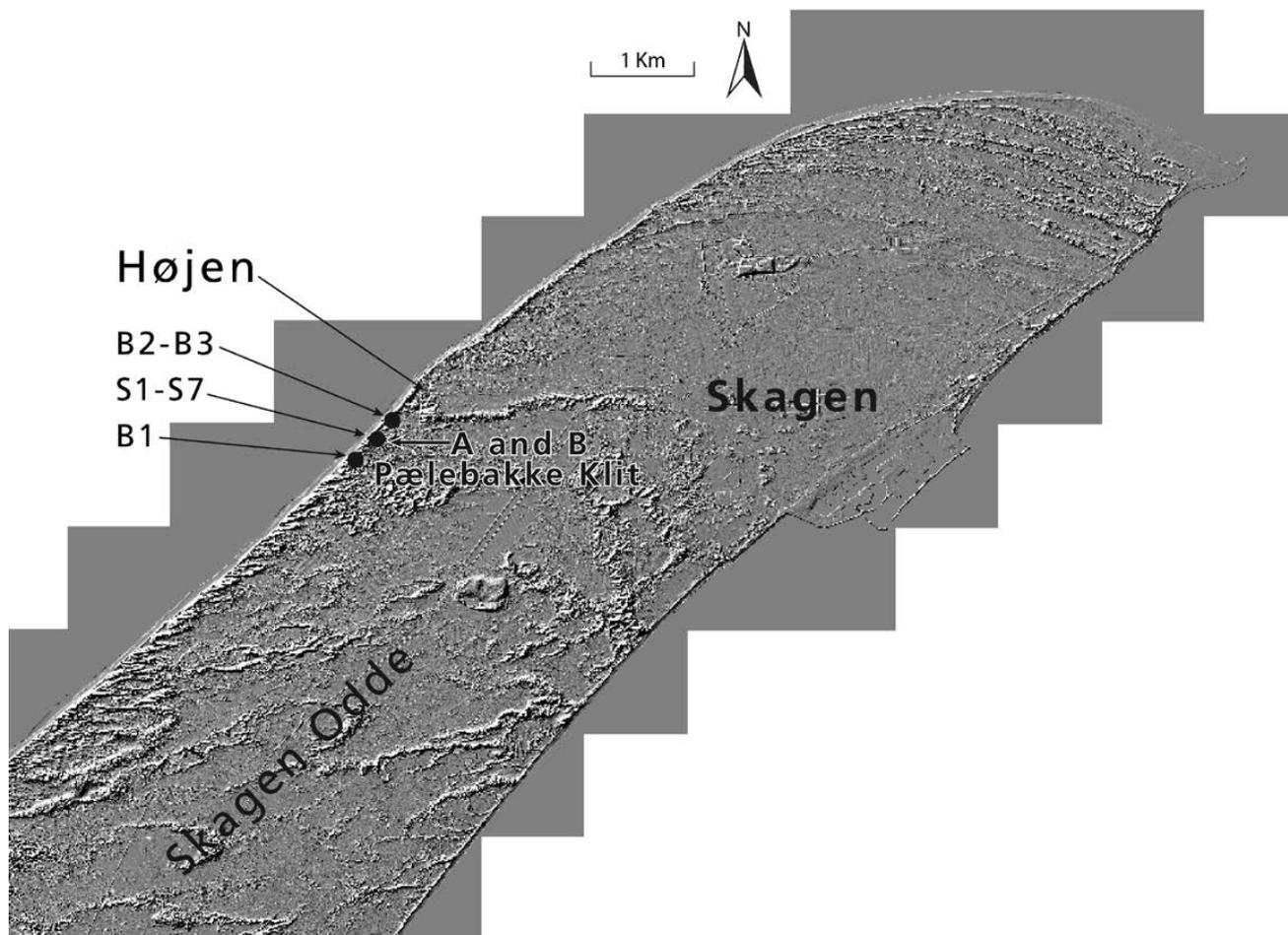


Fig. 2. LIDAR map of the northernmost part of the Skagen Odde spit system. Study area with sample sites at Pælebakke Klit (sites A and B, samples S1–S7), as well as sample sites for beach deposits (samples B1–B3), are indicated (Table 1). Note the slightly curved, W–E trending dune ridges and swales along the northwards facing and prograding spit coast, as well as active blowouts and incipient parabolic dunes along the westward facing and retreating coast south of Højen (see also Clemmensen *et al.* 2014). Coordinates (UTM zone 32; WGS 84): site A: E0589902, N6398834; site B: E0589889; N6398819.

overlain by a thin package of stratified beach sand. The beach deposits are at many places overlain by *martørv*; at the study area the *martørv* is only up to about 0.2 m thick, but elsewhere the *martørv* reaches thicknesses up to 1 m and locally 1.3 m (Clemmensen *et al.* 2001b). The aeolian sand that covers the *martørv* shows lateral variation in thickness and stratigraphy, but four units divided by thin soil horizons are recognized (Figs 3, 4). As the soil horizons locally are weakly developed or missing due to wind erosion at the beginning of the next aeolian phase, it is difficult to measure a complete succession at one site. The aeolian stratigraphy given here is therefore based on sedimentological observations at two closely situated sites (Figs 3, 4).

Skagen Odde is located in a cool, temperate climate region with an annual precipitation of 635 mm, a potential evaporation of 555 m/year, and an average temperature of 7.9° C (Scharling 2000). The Skagen Odde spit lies in a high-energy wind belt, and modern (AD 1991–2010) values for drift potential (DP) are as

high as 274 vector units (VU, m/s) or 2014 VU (knots) (Clemmensen *et al.* 2014). Resultant drift potential (RDP) is 142 VU (knots) or 1044 VU (m/s) and directed towards north-north-east. Storminess is relatively high and wind events of Beaufort 8 and higher occur with typical annual frequencies between 5 and 10 percent (Clemmensen *et al.* 2014).

Methods and sampling

This study is based on map information of shoreline history and dune development, field studies of aeolian sedimentology and geomorphology, and optically stimulated luminescence (OSL) dating of aeolian sand.

The first detailed map of the study area is the one in Resen's Atlas Daniscus from AD 1677 (see map on page 40 and 41 in Lønstrup & Nielsen 1995); then follows the map of The Royal Danish Academy of Sci-

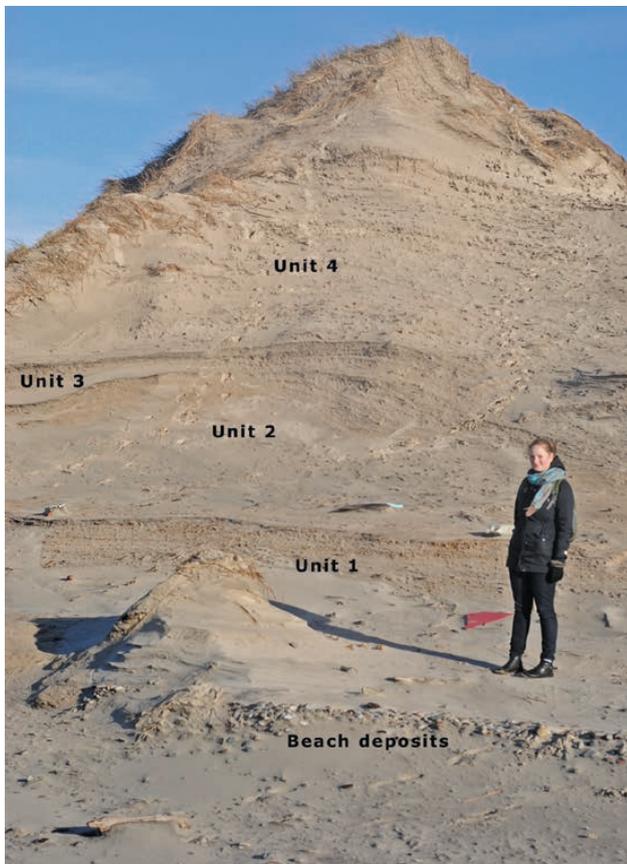


Fig. 3. Photo of coastal exposures at Pælebakke Klit (site B). Four aeolian sand units are recognized, divided by thin soil horizons. Note beach conglomerate at the base of the section. The beach deposits are overlain by swale peat, martør (not exposed on the photo). The base of the swale peat has an age around AD 500 (Clemmensen *et al.* 2001b).

ences and Letters from AD 1793, and topographical maps from AD 1887, AD 1968 and AD 1977 (source: Geodatastyrelsen; <http://eng.gst.dk>). The most recent development of the area is documented by orthophotographs.

Due to changing degrees of exposure (from almost completely covered by slope deposits to windswept and clean) it is rarely possible to restudy the same exposure. The study area was initially visited in May 2012 (site A; Fig. 2). martør at the base of the exposure was overlain by about 15 m of aeolian sand, and aeolian units 1, 2 and 4 were identified (Fig. 4). A closely situated section was studied in February 2014 and August 2014 (site B). Beach deposits and martør at the base were here overlain by about 15 m of aeolian sand, and aeolian units 1, 2, 3, and 4 were identified (Figs 3, 4).

Samples for OSL dating were collected in the two adjacent coastal sections (sites A and B). In section A, two samples (124803=S1 and 124802=S2) were taken

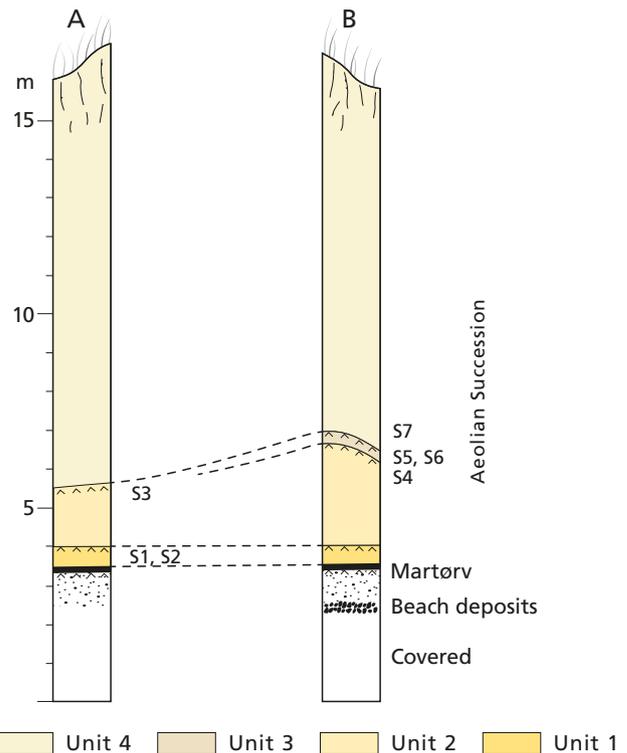


Fig. 4 Sedimentary successions at Pælebakke Klit (sites A and B). The distance between the two sites is around 20 m. Aeolian sand units 1–4 and OSL sample levels (S1–S7) are indicated. Soils are indicated by thin black lines and inverted v's. For details of OSL samples, see Table 1.

in unit 1, and one sample (124801=S3) was taken in unit 2 (Fig. 4; Table 1). In the closely situated section B, an additional sample (144701=S4) was taken in unit 2, two samples (144702=S5 and 144703=S6) were taken in unit 3, and one sample (144704=S7) was taken in unit 4 (Fig. 4; Table 1).

In the underlying marine spit sediment one OSL sample (024811=B1) was taken immediately south-west of sites A and B, and two OSL samples (024809=B2 and 094801=B3) were collected immediately north-east of sites A and B (Fig. 2). These OSL samples were collected in sandy beach deposits at the top of the marine succession approximately 0.5 m below the martør.

OSL samples were dated at The Nordic Laboratory for Luminescence Dating, DTU Risø Campus. For sampling procedures and dating methodology, see Clemmensen & Murray (2010). Results are shown in Table 1 where ages are given as years before dating in the laboratory; in the text the ages are also given as calendar years.

Table 1. OSL ages of sand samples from Pælebakke Klit, Skagen Odde

Risø no.	Field no.	Unit	Depth, cm	Age (Kyr) $\pm 1\sigma$	Dose (Gy)	n	Dose rate (Gy/Kyr)	w.c. %
124803	S1	AU 1	530	0.57 \pm 0.04	0.56 \pm 0.02	27	0.98 \pm 0.05	16
124802	S2	AU 1	530	0.53 \pm 0.04	0.52 \pm 0.02	26	0.98 \pm 0.05	11
124801	S3	AU 2	420	0.28 \pm 0.02	0.30 \pm 0.002	26	1.09 \pm 0.05	10
144701	S4	AU 2	560	0.237 \pm 0.015	0.255 \pm 0.006	24	1.08 \pm 0.06	12
144702	S5	AU 3	510	0.162 \pm 0.012	0.200 \pm 0.010	23	1.23 \pm 0.06	14
144703	S6	AU 3	510	0.130 \pm 0.009	0.152 \pm 0.008	23	1.17 \pm 0.06	14
144704	S7	AU 4	490	0.080 \pm 0.007	0.084 \pm 0.005	23	1.05 \pm 0.05	20
024811	B1	Be. dep.	500	1.87 \pm 0.16	1.97 \pm 0.14	27	1.05 \pm 0.05	5
024809	B2	Be. dep	500	1.83 \pm 0.15	1.88 \pm 0.10	30	1.03 \pm 0.06	5
094801	B3	Be. dep	500	1.35 \pm 0.09	1.80 \pm 0.06	29	1.33 \pm 0.07	4

AU: aeolian unit. Be. dep: underlying beach deposits. Depth is given as 50% of the present depth beneath the top of the cliff face as it is assumed that aeolian sand accumulated continuously over time. Year of dating is given by the first two figures in the Risø no., i.e. sample 124803 was dated in 2012. Gy: Dose measured in Gray units, the metric (SI) unit of absorbed radiation dose of ionizing radiation. n: number of aliquots measured to give the Dose. w.c.: water content.

Spit evolution

Spit growth

During the last 5000 years the spit has been growing to the north-east at a rate of 2–10 m/year, and since AD 1695 more than 2 km has been added (Clemmensen *et al.* 2001b; Hauerbach 1992). Spit growth was accompanied by the formation of slightly curved, W–E trending and coast-parallel dune ridges separated by low-lying swales (Nielsen & Johannessen 2008; Clemmensen *et al.* 2014; Fig. 2). Peat developed relatively quickly in these swales and was with time transformed into relatively dense *martørv*. Radiocarbon dating of selected swale peats along a 15 km stretch of the spit forms the basis for an age model of spit evolution (Clemmensen *et al.* 2001b). According to this model, swale peat (*martørv*) started to develop at the study site at about AD 500. It is not documented when swale peat formation ended, but it is likely that peat formation in the swale continued until the swale was covered by aeolian sand during the beginning of the LIA.

Age results

In this work, supplementary age control on the spit deposits that underlie the aeolian sediments is provided by the three OSL samples B1–B3 from the topmost part of the beach deposits immediately below the swale peat (Fig. 2). These samples (094801, 024809, 024811; B3, B2, B1) have ages of, respectively, 1350 \pm 90 years (AD 659 \pm 90), 1830 \pm 150 years (AD 172 \pm 150), and 1870 \pm 160 years (AD 132 \pm 170) (Table 1).

Formation of aeolian sand units

Between AD 500 and the initiation of large-scale aeolian sand movement, spit growth continued, and the studied site at Pælebakke Klit was gradually shifted

from a position at the relatively protected northward growing part of the spit to a position on the westward facing and more wind-exposed part of the spit. This shift in position also placed the study site in an area of coastal retreat.

Map information shows that the studied part of the coastal section has retreated landwards about 2.5 m/year since AD 1793 and about 1.3 m/year in most recent years. This indicates that the study area was situated almost 600 m inland when the map by The Royal Danish Academy of Sciences and Letters was measured in AD 1793 and therefore probably up to 1250 m inland 500 years ago. The map in Resen's Atlas Daniscus from AD 1677 shows a line of relatively tall frontal dunes along the west coast of the spit, grading inland into smaller and less well defined dunes; aeolian sand covered most of the spit already in AD 1677. The map from AD 1793 also indicates that most of the northern part of Skagen Odde was covered by aeolian sand and sand dunes. The map is, however, not detailed enough to show the geomorphological form of these inland dunes. On the topographical map from AD 1887 the inland dunes are named and their morphology is mapped in great detail with contour intervals of 5 feet (1.5 m). Most larger dunes are parabolic in shape and their morphology indicates that they have moved from the west toward the east; these dunes are only partly stabilized by vegetation. Comparisons of the map from AD 1887 with the maps from the 20th century indicate that vegetation cover has increased with time (Anthonsen *et al.* 1996) and most inland dunes are now to a large degree covered by vegetation; most dunes have not moved detectably since the end of the 19th century. Map and orthophoto studies also show that frontal dunes, wind gaps and incipient parabolic dunes along the north-western shore of the spit are shifted inland in pace with coastal retreat, but the incipient parabolic dunes do not de-

velop into true transgressive dunes (Clemmensen *et al.* 2014).

Sedimentological field studies indicate that the aeolian sand that lies on top of the *martørv* is composed of four units (Figs 3, 4). Unit 1 lies directly on top of the *martørv* and is up to 1 m thick. It forms a sheet-like to low-relief undulatory sand unit and is covered by a 2–10 cm thick peaty soil horizon underlain by a dense network of roots. The sand has a pale yellowish grey colour (Fig. 3), is medium-grained with a mean grain size of 0.27 mm and is well sorted (moment sorting=0.36). The main part of the sediment is characterized by horizontal to low-angle stratification, but locally steeper dipping sets are developed. The stratification is outlined by subtle variations in grain size with the coarsest grains concentrated in thin layers. The sediment of unit 1 is interpreted as a sand accumulation formed by inland sand drift and dune migration. Similar low-angle stratified aeolian sheet sand and associated cross-stratified dune deposits have been described from Holocene dunefield deposits in Thy, north-western Denmark, and are also related to inland sand movement (Clemmensen *et al.* 2001a; Pedersen & Clemmensen 2005).

The second aeolian sand unit is up to 3.0 m thick and is covered by an immature soil. It forms a sheet-like to low-relief undulatory unit (Figs 3, 4). The sand has a pale yellowish grey colour, is medium-grained with a mean grain size of 0.29 mm and is well sorted (moment sorting=0.36). The main part of unit 2 is characterized by low-angle stratification, but in its upper part convex-up cross-bedding with steeper dip angles is developed. Also this unit is interpreted to

have formed by inland sand drift and dune migration.

Aeolian unit 3 is only locally developed. It lies between the two incipient soil horizons (Figs 3–4) and has a thickness of about 0.5 m; it has a pale yellowish grey colour, is medium-grained with a mean grain size of 0.29 mm and is well sorted (moment sorting=0.36). Also this unit is characterized by low-angle to convex-up stratification, and the stratification seems to drape the underlying incipient soil. Sedimentary structures have typically been obliterated in its upper part due to soil formation and the presence of small roots.

The uppermost aeolian sand unit is up to 10 m thick and its upper part forms the modern frontal dunes (Figs 3, 4). The sand is fine- to medium-grained; a sample from the base of the unit has a mean grain size of 0.28 mm and is well sorted (moment sorting=0.36). The sand is paler than the underlying aeolian sand; it has horizontal and low-angle stratification but eastward dipping cross-strata are also present, particularly in the uppermost part of the unit. The sediment of unit 4 formed by accumulation of sand on the frontal dunes and on closely associated dome-shaped dunes. Cross-strata structures indicate inland transport of sand.

Age results

OSL dating results are shown in Table 1. Two closely spaced samples in aeolian sand unit 1 (S1 and S2, site A) gave ages of 570±40 years (AD 1442±40) and 530±40 years (AD 1482±40), respectively. Two samples in aeolian unit 2 (S3, site A, and S4, site B) gave ages of 280±20 years (AD 1732±20) and 237±15 years (AD 1777±15), respectively. Two closely spaced samples in

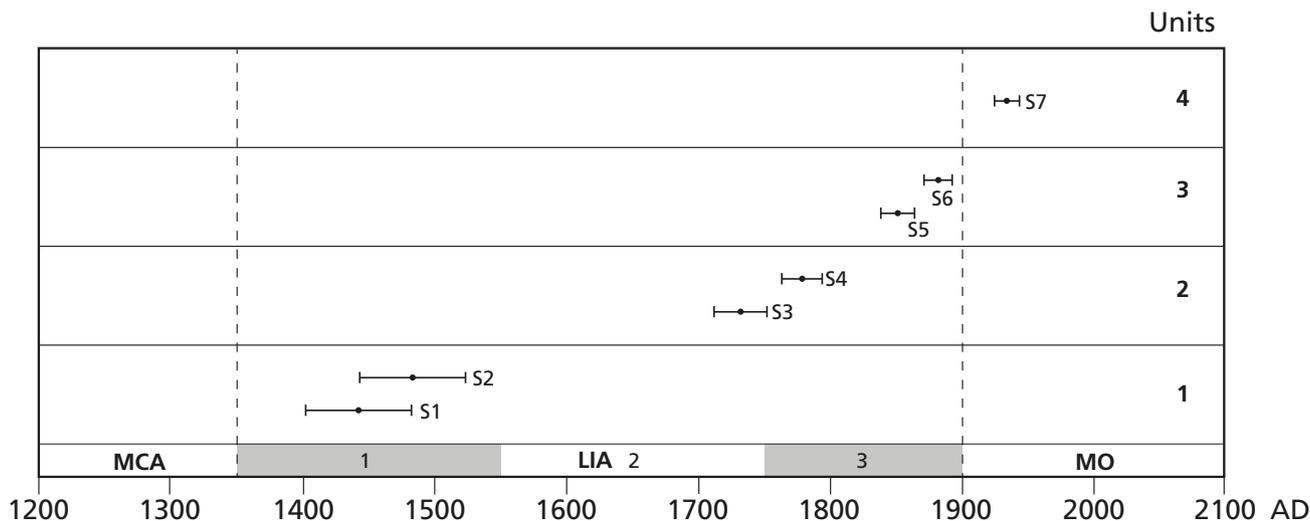


Fig. 5. OSL ages of the aeolian sand units, Pælebakke Klit. Calculated ages are given as small dots with error bars. Note that the first three units were deposited during the the Little Ice Age (LIA) while the fourth unit is modern. Units 1–3 are well separated in time, suggesting episodic aeolian sand movement during the LIA. MCA=Medieval Climatic Anomaly; MO=Modern Climatic Optimum. Climatic subdivision of LIA into stormy phases 1 and 3 (grey), and a relatively calm phase 2 (white) is indicated (Hass 1996).

unit 3 (S5 and S6, site B) gives ages of 162 ± 12 years (AD 1852 ± 12) and 130 ± 9 years (AD 1884 ± 9), respectively, and one sample (S7, site B) from the basal part of the frontal dune unit (unit 4) gave an age of 80 ± 7 years (AD 1934 ± 7) (Fig. 4; Table 1).

Discussion

Timing of events

The stratigraphy of the study site and the OSL dating results suggest that inland sand movement and transgressive dune formation took place in three phases prior to the most recent formation of frontal dunes (Fig. 5). Each episode of sand mobilization was separated by a phase of stabilization or near-stabilization of the aeolian landscape as suggested by the thin soil horizons of which the lowermost one is best developed. The three phases of aeolian sand movement all fall within the climatic period defined as the Little Ice Age (LIA). The Little Ice Age was the most recent cold period in much of the North Atlantic region; it followed the warm period during the Medieval Climate Anomaly (MCA; Fig. 5) (Trouet *et al.* 2012). The duration of the LIA has been defined differently by different authors. According to Hass (1996), the LIA covers the time span between AD 1350 and AD 1900; Trouet *et al.* (2012) places the LIA between AD 1400 and AD 1800, while Clarke & Rendell (2009, 2011) restrict the LIA to the time period between AD 1570 and AD 1890 (1900). Data from raised peat bogs in south-western Sweden suggest that the LIA took place between AD 1350 and AD 1850 (Björck & Clemmensen 2004). We here follow the definition of Hass (1996) and define the LIA to cover the time span between AD 1350 and AD 1900.

Multi-proxy data on temperature on the northern hemisphere indicate that there were climatic fluctuations during the LIA, and a reconstruction of climate change during the last 2000 years by Christiansen & Ljungquist (2012) shows that the MCA peaked around AD 1000; thereafter temperature decreased stepwise with cold intervals around AD 1300, AD 1450, and AD 1650. After AD 1650 temperatures increased again but there was a final cold interval around AD 1850. According to Hass (1996), there were three climatic periods during the LIA: a first phase between AD 1350 and AD 1550 with increased storminess, a second phase between AD 1550 and AD 1750 with decreased storminess, and a third phase between AD 1750 and AD 1900 again with increased storminess (Fig. 5).

Large-scale sand movement and transgressive dune formation at the northernmost part of Skagen Odde is

here interpreted to have started around AD 1460 (the mean age of samples S1 and S2; Fig. 5). The preservation of low-relief dune forms in the lowermost unit indicates that at least part of the sand movement inland was related to dune migration. Modern dunes in the northern part of Skagen Odde have mean grain sizes between 0.20 and 0.23 mm (Clemmensen *et al.* 2014) and are thus more fine-grained than the sand of the lower sand unit. This is tentatively taken to indicate that inland transport of sand during formation of the lowermost sand unit took place during strong winds.

As the study site was probably situated up to 1250 m inland 500 years ago (see above), it can be deduced that sand movement at the coast most likely was initiated earlier than around AD 1460. Knowing that the modern parabolic dune Råbjerg Mile migrates around 10 m inland per year (Anthonsen *et al.* 1996), it is inferred that inland sand movement at the coast near Højen may have started 125 years earlier or around AD 1335. If the sand moved inland as sand drift (sand sheets), however, sand could have shifted inland much faster. According to Pye & Tsoar (2009), sand grains in the 0.28–0.48 mm size range have a mean forward velocity of 0.6–1.8 cm/s during sand drift. Using 1 cm/s as a preferred value, inland movement of sand could be as much as 860 m per day, indicating that sand drift initiated at the coast could reach the study site in about two days. Such a rapid inland transport of sand is of course unlikely as existing vegetation and topography would have slowed down the sand drift, but it is possible that sand could have been transported inland from the coast to the study site within a few years.

Historical reports first mention sand drift on Skagen Odde around AD 1571 (Brüel 1918; Hansen 1964). Farther south along the west coast of Jutland there are reports of sand drift around AD 1553 (Brüel 1918). The new OSL dates indicate that the first phase of sand movement started somewhat earlier than mentioned in historical records.

The second phase of inland sand movement and transgressive dune formation is documented by OSL ages from both sites and is interpreted to have taken place between AD 1730 and AD 1780 (Fig. 5). The study area was then situated some 700 m inland, suggesting that sand movement at the coast could have started 70 years earlier or around AD 1660. This is in agreement with historical sources that mention severe sand drift in the middle and later part of the 17th century (Brüel 1918; Hansen 1964). If sand movement was associated with sand drift and sand sheet formation, inland movement could be much faster as discussed above. Sand unit 2 at Skagen Odde is coarser grained than modern dune sand in the area, suggesting that inland transport was linked to strong winds. Sand movement on Skagen Odde during this second phase was

severe and sand reached the Sanct Laurentii Church near the town of Skagen around AD 1775; the church was abandoned in AD 1793. As the distance between the study site and the church is about 2800 m in a downwind direction, it is likely that sand from nearby sources (stabilized or partly stabilized dunes) was reactivated during this event. This second phase of sand movement may have affected large coastal parts of northern Jutland, and the basal part of aeolian sand in the cliff-top dune at Rubjerg Knude (a coastal cliff 55 km south of the study area; Fig. 1) has an OSL age of 274 ± 14 years (AD 1726+14) (Saye *et al.* 2006).

The third episode of sand movement is dated to around AD 1868 (mean age of samples S5 and S6; Fig. 5). As the study area 150 years ago was situated only some 375 m inland, this event only records limited inland transport of sand from frontal dunes and closely situated dome-shaped dunes. Also this episode may have affected a large part of Skagen Odde, and a sample from the basal part of an uppermost aeolian dune unit 10.9 km south of Pælebakke Klit has an age of 189 ± 11 years or AD 1876 \pm 11 (Clemmensen & Murray 2010).

The fourth and final episode of sand movement is related to the formation of frontal dunes along the present coast. OSL dating at the base of this unit at site B indicates that these frontal dunes started to develop around AD 1934 (Fig. 5). However, as these frontal dunes are a type of roll-over dunes constantly reforming inland in pace with coastal retreat, this date only yields an age of the oldest frontal dune material presently preserved in the exposure.

Thus it is concluded that there were three phases of aeolian sand movement on Skagen Odde during the

LIA; the first one was initiated around AD 1460 (or possible as early as AD 1335), the second phase was initiated around AD 1730 (or possible already around AD 1660), while the third phase took place around AD 1870. Sand drift was episodic as indicated by the development of thin soils. The soil separating unit 1 and 2 is best developed, suggesting that after the first sand drift event the dune landscape became stabilized or near-stabilized. Judged from the new OSL dates this period of near-stabilization took place after AD 1550 but before AD 1700.

Causes and climate connections

Having established that sand invasion on Skagen Odde during the LIA took place in three main phases, it remains to be discussed what caused the sand mobilization and how these phases of sand movement may be linked to climate and/or anthropogenic influence. Skagen Odde lies in a high-energy wind climate, but observational and instrumental data indicate that the wind climate has varied a lot the last 150 years (Clemmensen *et al.* 2014). The storminess level was extremely high around AD 1870 and has been decreasing since then. Also the drift potential (DP) was outstandingly high around AD 1870, reaching annual values of 9600 VU (knots), while the DP levels were around 2000–2500 VU over the last decades and are still decreasing (Clemmensen *et al.* 2014). Yizhaq *et al.* (2009) found that dunes are typically active when DP values are higher than 2000–3000 VU (knots), irrespective of yearly precipitation. In agreement with these data, dunes on Skagen Odde have been stabilized during the last 150 years in response to the

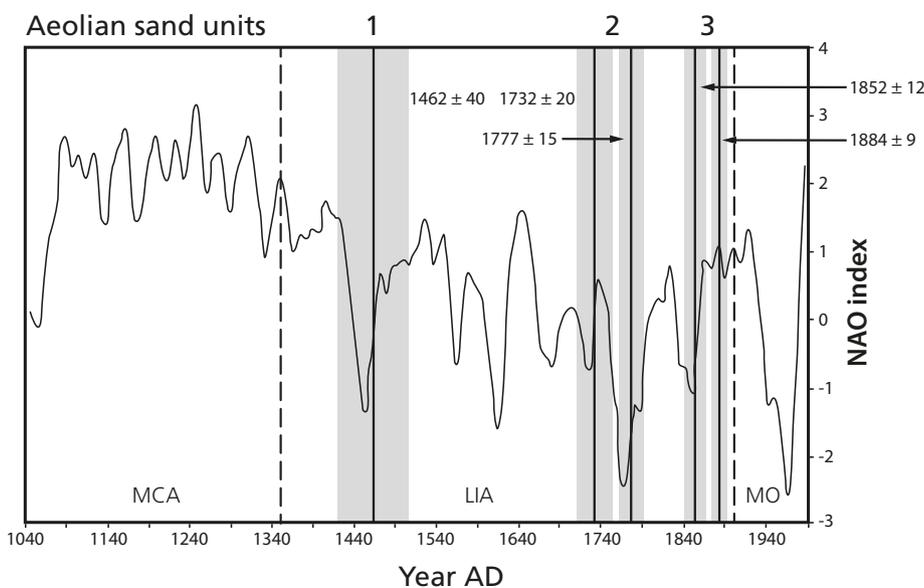


Fig. 6. Values of the North Atlantic Oscillation (NAO) index versus the ages of the first three phases of aeolian sand movement (units 1–3), Pælebakke Klit. The age of the first event is given as the mean of samples S1 and S2 as they overlap in age. The grey bands are the uncertainty intervals. MCA=Medieval Climatic Anomaly; MO=Modern Climatic Optimum. The three phases of aeolian sand movement occurred after AD 1460 during the LIA when overall NAO index values were low. In particular the first phase of sand movement around AD 1460 is clearly linked to a marked drop in NAO index. NAO index values from Trouet *et al.* (2012).

decrease in storminess and dune management work (Clemmensen *et al.* 2014). In the same period Råbjerg Mile has changed form from a crescentic dune to a parabolic dune (Anthonson *et al.* 1996).

The third phase of aeolian sand movement (unit 3), dated to have taken place around AD 1870, occurred during an interval when wind energy was exceptionally high at Skagen Odde (Clemmensen *et al.* 2014). Sand activation took place in spite of ongoing coastal dune management. If this third event is taken to be representative for the two earlier events, it may be inferred that also these events were linked to an exceptional high-energy wind climate. Judged by the amount of sand that was shifted inland during the first two events, storminess then may have been even higher. In addition, the removal of parts of the vegetation on the frontal dunes by local inhabitants during the early and middle part of the LIA made these dunes more vulnerable to remobilization. In support of a cultural imprint, especially on the first sand drift event, is the fact that the Danish King Christian III in AD 1539 promulgated a law forbidding the removal of vegetation in the dunes, implying that dune vegetation may have been partly removed at the beginning of the LIA (Kjærgaard 1994).

According to Trouet *et al.* (2009, 2012), the transition from the MCA to the LIA was characterized by a major change in atmospheric circulation. A reconstruction of the North Atlantic Oscillation (NAO) index from proxy data shows that NAO values were positive during the MCA and that there was a marked drop to negative values around AD 1450, at the beginning of the LIA (Fig. 6). NAO values fluctuated between negative and moderately positive during the LIA. Intervals with particularly negative values are seen around AD 1620 and AD 1760. During intervals with persistent positive NAO values, enhanced winter storminess is assumed to influence north-western Europe (Trouet *et al.* 2009, 2012). In contrast, blocking anticyclones at mid-latitudes during negative NAO values should result in decreased winter storminess. However, according to Trouet *et al.* (2012), periods of negative NAO values as seen frequently during the LIA are also characterized by an increased intensity of the cyclones.

Van Vliet-Lanoë *et al.* (2014) relate storminess during the late Holocene to variations in NAO as well as in the Atlantic Multidecadal Oscillation (AMO). The AMO describes variations in the sea surface temperatures of the North Atlantic Ocean. Cool (negative AMO) and warm (positive AMO) phases alternative on decadal scale.

According to Van Vliet-Lanoë *et al.* (2014), increased storminess in the North Atlantic region is linked to two different climatic scenarios: negative NAO mode combined with positive AMO values, and negative NAO mode combined with negative AMO mode. The first climatic scenario characterized the period between AD 1830 and AD 1890 (Van Vliet-Lanoë *et al.* 2014) and could probably explain the enhanced storminess around AD 1870 documented by wind data from Skagen Odde (Clemmensen *et al.* 2014) and by the new OSL ages. A similar climatic setting may also explain the enhanced storminess at Skagen Odde between AD 1730 and AD 1780 deduced from the new OSL dates, as much of the 18th century was characterized by a negative NAO mode (especially around AD 1750) but also had a number of prominent positive AMO events (Trouet *et al.* 2012; Van Vliet-Lanoë *et al.* 2014). The second climatic scenario characterizes the period between AD 1400 and AD 1480 when both the NAO and AMO modes were negative (Trouet *et al.* 2012; Van Vliet-Lanoë *et al.* 2014). Enhanced storminess and the initiation of the first aeolian sand movement at Skagen Odde can probably be linked to this second climatic setting. Studies of wind data at Skagen Odde since AD 1860, however, indicate that there are no statistical links between storminess and NAO and AMO variation on an annual basis (Clemmensen *et al.* 2014). It may therefore be that storminess variation is controlled by decadal or longer term variation in NAO and AMO values, as suggested in this study.

Regional significance

In order to test the regional importance of the new age determination of the initial phase of the LIA event of aeolian sand movement, care should be taken when looking at OSL ages of dune sand because, due to reworking as in most Danish examples, many north-

Table 2. Proxy data of North Atlantic storminess during the beginning of the Little Ice Age

Locality	Data	Age	Reference
Skagen, Denmark	Aeolian sand, coastal dunefield	Around AD 1460	This paper
Wadden Sea, Denmark	Aeolian sand, salt marsh deposits	Around AD 1460	Szkornik <i>et al.</i> 2008
Outer Hebrides, Scotland	Aeolian sand, coastal peat mosses	After AD 1400	Dawson <i>et al.</i> 2004
Halland, Sweden	Aeolian sand, raised peat bogs	Around AD 1475	Björck & Clemmensen 2004
Iceland	Loess profiles	Around AD 1500	Jackson <i>et al.</i> 2005

Ages date onset of aeolian sand movement presumably linked to increased storminess. See text for details.

west European coastal dune deposits would rarely be expected to give the age of the first sand movement. Published dates therefore in most cases would postdate the initiation of sand movement. As an example, transgressive dunes on the barrier island Rømø in the southern part of the Danish Wadden Sea (Fig. 1) have ages of 270 years (AD 1740) and 370 years (AD 1640), and these ages most likely postdate the initiation of aeolian sand movement because the old beach surfaces on top of which the dunes were deposited have ages between 630 years (AD 1380) and 690 years (AD 1320), cf. Madsen *et al.* (2007).

More reliable regional evidence of the initial LIA event would therefore arise from studies of sedimentary archives with relatively continuous and complete records of late Holocene aeolian activity (Table 2). One such record is provided by raised peat bogs in Halland, south-western Sweden. These bogs contain a continuous record of aeolian sand influx (ASI) through time and also cover the transition from the MCA to the LIA. This time interval was characterized by increased aeolian sand influx to the bogs with a first pronounced ASI peak around AD 1475 (Björck & Clemmensen 2004). There was a second pronounced ASI peak around AD 1720 (De Jong *et al.* 2006; Raible *et al.* 2008). These peaks of increased sand influx to the raised bogs, and in particular the abundance of medium-sized sand grains, were used as proxies for storm frequency and intensity. Thus, there is a good match between the timing of onset of sand drift on Skagen Odde around AD 1460 and increased aeolian sand influx to the peat bogs in south-western Sweden around AD 1475.

A second reliable record in this connection comprises aeolian soil profiles in Iceland. Grain size studies of these soil profiles have indicated a number of intervals with increased grain size related to cold and stormy intervals during the Holocene; the last of these intervals was initiated around AD 1500 (Jackson *et al.* 2005). Supplementary evidence on this early event of sand movement is given by aeolian sand layers embedded in fine-grained coastal deposits. An aeolian sand sheet buried in salt marsh deposits in the northern part of the Danish Wadden Sea (Fig. 1) was deposited between AD 1460 and AD 1540 (Szkornik *et al.* 2008). Finally, Dawson *et al.* (2004) examined landward tapering layers of wind-blown sand in coastal peat mosses in the Outer Hebrides, Scotland. These aeolian sand layers are considered to constitute well dated records of increased storminess and many were first produced after AD 1400 at the onset of the LIA (Dawson *et al.* 2004).

Thus, five records from aeolian sediments across large regions in the North Atlantic consistently indicate an increase in storminess between AD 1400 and 1500 (Table 2) around the onset of overall negative NAO

values at the beginning of the LIA. The aeolian records are supplemented by data from high-energy estuaries in northern France indicating that an important storm phase in the North Atlantic was initiated around AD 1500 (Sorrel *et al.* 2012).

The new data from Skagen Odde indicate renewed sand movement between AD 1730 and 1780, and around AD 1870. OSL dating of the basal part of aeolian sand sheets suggests that these latter episodes of sand movement also affected areas on the Danish west coast of Jutland south of the study area. However, the chronology of these episodes in a wider regional perspective is poorly known as existing OSL ages of dune sand typically postdate the onset of sand movement.

Conclusions

Sedimentological studies of coastal sections along the north-western part of the Skagen Odde spit system, Denmark, reveal the presence of four aeolian sand units overlying late Holocene beach deposits.

Optically stimulated luminescence (OSL) dating of samples from the coastal exposures indicate four phases of aeolian sand movement: around AD 1460, between AD 1730 and 1780, around AD 1870, and since about AD 1935.

Sand movement in the first three phases occurred during the Little Ice Age and was related to extensive inland dune migration during this period. Periods of stabilization or near-stabilization of the dune landscape separated the three phases of aeolian sand movement. The final fourth phase represents the recent formation of frontal dunes and related coastal retreat.

The first phase of sand movement around AD 1460 was initiated during the beginning of the Little Ice Age. Negative North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) at the same time apparently caused a change in the atmospheric circulation leading to more severe cyclones forcing sand to move inland and build dunes.

Both the second and third phase of aeolian sand movement occurred during the Little Ice Age during increased storminess; however they are distinguished from the first phase as negative NAO values probably were linked to positive AMO values during these periods.

Aeolian sand movement during the first phase (AD 1460) at Skagen Odde is in accordance with regional studies of aeolian activity in the North Atlantic, indicating extensive changes in the atmospheric circulation around that time.

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