# **Climate Archive Dune**

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## Summary

The aim of this study was to access a new archive of temporal wind-field variations recorded in the sedimentary succession of a migrating dune. Dunes are sensitive systems which can reveal environmental variations, such as changes in wind-field variations, vegetation cover or sediment supply, by reflecting changes in dune morphology, internal architecture and/or grainsize variations. Therefore, they are valuable palaeoclimatic archives.

An integrated approach combining geophysical, sedimentological and statistical tools was applied. First, an age model was developed combining optically-stimulated luminescence (OSL) dating and aerial images. Afterwards, the dune development over time and the internal geometry were reconstructed based on observations from aerial images and data obtained with a ground-penetrating radar (GPR). Finally, proxies for wind-field variations were obtained from granulometric measurements of approximately 5000 sediment samples. The granulometric measurements were compared with a time series of meteorological data. A function correlating both datasets enabled the reconstruction of wind-speed variations in a time period without instrumental data.

The results of the age model based on OSL ages compared to an independent age model based on aerial images showed that the five oldest samples agreed the independent age estimates. However, the six youngest samples presented a systematically overestimation of 10 to 40 years due to a combination of small thermal transfer and incomplete bleaching in the medium and slow OSL component.

The aerial images showed that the dune changed from a transverse to a parabolic dune. Variations of the migration rates depend on wind speeds exceeding values of 3 Beaufort and on the annual precipitation. The GPR showed a geometrical change from tabular to convex foreset geometry associated to the geomorphological change of the dune. It also revealed erosional unconformities associated with a period of long lasting easterly storms. Toplap geometries were interpreted to represent periods of higher wind direction variability.

The correlation between the geological and the meteorological record showed that fine and well sorted sediment were related to low wind speeds, whereas coarse and poorly sorted sediment were associated to high wind speeds. A mathematical function describing this relation allowed for the reconstruction of wind-speed variations in the absence of instrumental data on

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a decadal timescale. Furthermore, sedimentological and meteorological records showed an annual cyclicity expressed by a change in sediment sorting from well to poorly to well sorted, and a change in wind speed from low to high to low, respectively. Additionally, a 3.6 and a 5 yr cycle in the sedimentological record and a 6.5 and 8 yr cycle in the wind-speed record were also observed, most likely associated to the North Atlantic Oscillation (NAO).

In summary, it has been shown that sediments of a migrating dune bear a unique and valuable record of past wind-field conditions. The time series based on granulometric analysis enable the reconstruction of wind speed with values higher than 7 m/s back to 1907. This reconstruction showed that the periods with stronger winds took place at the end of the first decade, beginning and end of the second decade, second half of the 1930s, mid-to-late 1940s, mid-to-late 1950s, and from the mid 1960s to 2003. Migration rates, erosional unconformities, toplap geometries, and geomorphological changes were presumed to be related to specific wind and precipitation conditions.

## Zusammenfassung

Die vorliegende Arbeit zeigt, dass Änderungen des lokalen Windfeldes in der sedimentären Abfolge einer küstennahen Wanderdüne archiviert werden. Dünen sind sensible Systeme, die unmittelbar auf Windfeldvariationen reagieren. Weitere Einflussfaktoren, wie Veränderungen in der Vegetation oder der Sedimentzufuhr, spiegeln sich in einer varianten Dünenmorphologie, der internen Architektur und im Korngrößenspektrum wider. Aus diesen Gründen, sind Dünen ein wertvolles paläoklimatisches Archiv.

Ein integrierter Ansatz aus geophysikalischen, sedimentologischen und statistischen Methoden stand für die Bearbeitung der Aufgabenstellung zur Verfügung. Die Kombination aus optisch stimulierter Lumineszenz (OSL), eine Methode der absoluten Altersdatierung, und Luftbildern ermöglichte ein vielschichtiges Altersmodell. Auf dieser Grundlage konnte die zeitliche Entwicklung der Düne rekonstruiert werden. Die interne Geometrie, die anhand von Georadardaten (ground-penetrating-radar, GPR) ermittelt wurde, liegt mit Hilfe des Altersmodells in einem zeitlichen Kontext. Granulometrische Messungen von etwa 5000 Sedimentproben fungieren als Proxies für Windfeldvariationen. Die Analyse der Korngrößenparameter wurde mit einer Zeitreihe von meteorologischen Daten verglichen. Eine Funktion, die beide Datensätze korreliert, ermöglichte die Rekonstruktion der Windgeschwindigkeitsvariationen in einem Zeitraum ohne aufgezeichnete Daten.

Die Resultate des OSL Altersmodells verglichen mit den Luftbildern zeigen, dass die fünf ältesten OSL Proben mit den Ergebnissen der Luftbildauswertung übereinstimmen. Die sechs jüngsten Proben zeigen dagegen eine systematisch Überschätzung von 10 bis 40 Jahren, was auf eine Kombination von kleinen Thermotransferereignissen und unvollständiger Bleichung in der Mittel- und Langsam-OSL-Komponente zurückgeführt wird.

Die Auswertung der Luftbilder gibt, neben einer Alterseinteilung, ein Bild der geomorphologischen Entwicklung wider und weist Änderungen in der Migrationsgeschwindigkeit der Düne nach. Die aktive Düne veränderte sich seit dem ersten zur Verfügung stehenden Luftbild aus dem Jahr 1936 aus einer Querdüne hin zu einer Parabeldüne. Änderungen in der Migrationsrate sind abhängig von Windgeschwindigkeiten über 3 Beaufort und den jährlichen Niederschlägen. Die Auswertung der GPR-Daten zeigt eine geometrische Veränderung von flachen hin zu konvexen foresets. Der Wechsel in der Geometrie geht mit der geomorphologischen Änderung der Düne einher. In den Radarlinien ermittelte Erosionsdiskordanzen treten während andauernder

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östlicher Stürme auf. Toplap-Geometrien repräsentieren Perioden mit einer höheren Variabilität der Windrichtung.

Die Korrelation zwischen den sedimentologischen und meteorologischen Aufzeichnungen zeigt, dass feines und gut sortiertes Material mit niedrigen Windgeschwindigkeiten einher gehen, während grobes und schlecht sortiertes Sediment mit hohen Windgeschwindigkeiten korrelieren. Eine mathematische Funktion, die diese Beziehung beschreibt, erlaubt die Rekonstruktion der Windgeschwindigkeitsvariationen in Abwesenheit von instrumentellen Daten auf einer dekadischen Zeitskala. Mit Hilfe der beiden Datensätze konnte eine jährliche Zyklizität festgestellt werden. Dabei ändert sich die Sortierung des Sediment von gut zu schlecht und wieder zu gut simultan mit der Windgeschwindigkeits von niedrig zu hoch zu niedrig. Darüber hinaus wurden ein 3.6- und ein 5-Jahres-Zyklus in der sedimentologischen Abfolge und ein 6.5- und 8-Jahres-Zyklus im Windgeschwindigkeits-Rekord beobachtet, die wahrscheinlich Änderungen in der Nordatlantischen Oszillation (NAO) zugeordnet werden können.

Die Auswertung des umfangreich vorhandenen Datensatzes zeigt, dass Sedimente einer Wanderdüne ein einzigartiges und wertvolles Archiv für Windfeldvariationen liefern. Auf Korngrößen basierende Zeitreihen ermöglichen die Rekonstruktion von Windgeschwindigkeit mit Werten höher als 7 m/s zurück bis zum Jahr 1907. Perioden mit stärkeren Winden treten am Ende des ersten Jahrzehnts, am Beginn und Ende des zweiten Jahrzehnts, in der zweiten Hälfte der 1930er Jahre, Mitte bis Ende der 1940er Jahre, Mitte bis Ende der 1950er Jahre, und ab Mitte der 1960er Jahre bis 2003 auf. Änderungen in der Migrationsgeschwindigkeit, Erosionsdiskordanzen, Toplap-Geometrien und geomorphologische Veränderungen wurden mit bestimmten Wind- und Niederschlagsverhältnissen korreliert.

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## **Chapter 1**

## Introduction

Coastal dunes are accumulations of sand deposited by wind, and are present generally in temperate and humid environments. Their development depends mostly on the wind speed and direction and sediment supply, although vegetation plays also an important role on certain types of dunes (Goldsmith, 1978; Pye, 1983; Orford et al., 2000; Anthony et al., 2010). Aeolian processes and landforms are the result of interactions between wind and land surface, and consequently they are sensitive to changes in atmospheric parameters and surface conditions (Lancaster, 1994). Therefore, dunes represent valuable climate archives.

Each type of dune records a unique pattern of growth as it migrates (McKee, 1979). Due to the sensitivity of aeolian dunes to environmental pressures, the record of their growth can present anomalies or irregularities. Thus, it is important to understand what drives those anomalies and the corresponding changes in internal dune structures (Girardi and Davis, 2010). Nowadays, the use of the ground-penetrating radar (GPR) is widely extended for investigating the internal architecture of dunes. The GPR allows to explore the shallow subsurface (< 50 m) with a centimetre to decimetre resolution, enabling the visualization of dune stratigraphy. Several investigations have used the GPR to link features of the internal structure of the dunes to climatic and environmental changes (Havholm et al., 2004; Buynevich et al., 2007; Cunningham et al., 2011; Costas et al., 2012). Such studies are possible because the historic growth of dunes is recorded in each dune by a deposition of sand over the dune crest. Successive depositions of sand over the dune crest. The dune as it migrates. The history of these climatic events and anthropogenic pressures is recorded in the buried stratigraphy or internal structure of the dunes, analogous to how tree rings record environmental conditions (Girardi, 2005).

The establishment of a high-resolution chronology is essential to have a better understanding of the processes recorded in the dunes. Aerial imagery is a fundamental tool for complementing the

information about internal dune geometry obtained with the GPR, since it provides information about dune growth, vegetation cover, and migration (Bailey and Bristow, 2004; Hugenholtz and Wolfe, 2005; Hugenholtz et al., 2008; Girardi and Davis, 2010). Additionally, optically-stimulated luminescence (OSL) dating has demonstrated to be the appropriate tool to date very young sediments (< 100 years) (Murray and Olley, 2002; Ballarini et al., 2003; Madsen et al., 2007; Madsen and Murray, 2009). However, some problems associated to the dating of very young sediments should also be taken into account. These problems are associated to insufficient luminescence sensitivity to allow measurement when very low doses are involved, resulting in a low signal-to-noise ratio and imprecise doses; significant thermal transfer during the thermal pre-treatment that takes place prior to the OSL measurement; incomplete resetting of the sediments, causing an overestimation of the OSL age; and an alteration of the sedimentary environment due to changes in the water content, sediment matrix or sample depth, resulting in a time-dependent dose rate (Madsen and Murray, 2009). Therefore, a comparison with an independent age control based on aerial images or cartographic maps can result beneficial.

It is well know that migrating dunes reflect current climate conditions, such as precipitation, wind strength, and direction. Therefore, developing an integrated approach combining geophysical, sedimentological, and statistical tools can help revealing the archives of wind-field changes recorded in migrating dunes. Accessing to these archives could be of great relevance for palaeoclimatic models investigating changes of wind speed and direction.

#### 1.1. Dune classification

Dune morphology is characteristic of the environment where they are present. Therefore, when classifying dunes the factors affecting their development, such as sediment availability, wind strength and direction, and vegetation should be considered. Tsoar et al. (2004) mentioned that there is no accepted classification that refers to all known dune types, but according to the directional variability of the winds they presented a general classification considering three groups: migrating dunes, in which the whole dune body advances with little or no change in shape and dimension; elongating dunes, in which the dunes become extended in length with time; and accumulating dunes, in which the dunes have little or no net advance or elongation.

McKee (1979) classifies individual dunes in terms of the number and position of slip faces, under the assumption that the number of slip faces corresponds to the number of dominant wind directions in the local wind regime. The three major groups are simple, compound, and

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complex dunes. The simple dunes are individual forms, spatially separated from their neighbours. Compound dunes are two or more dunes of the same type combined by overlapping or being superimposed on one another. Complex dunes are two different simple types of dunes which have merged or grown together.

Besides these general classifications, several dune varieties can be defined. The most conspicuous varieties are:

 Barchan dunes: which are characterised by having a crescentic shape and horns pointing downwind (McKee, 1979).

 Linear or seif dunes: which are characterised by their considerable length, by having one or two lee faces, being relative straight, parallel to other similar ridges and separated from them by interdune areas (McKee, 1966; Mountney, 2006).

- Transverse: they are straight sand ridges, oriented perpendicular to the dominant wind and with a single slip face (McKee, 1966; Mountney, 2006).

 Parabolic: they are characterised by a U-shape or V-shape, in which the middle part has moved forward with respect to the arms. The arms are frequently anchored by vegetation (McKee, 1966).

- Star dunes: they present a pyramidal morphology with a central point from which three or more arms radiate in different directions (McKee, 1979; Mountney, 2006).

- Dome dune: they are low, circular dunes, with a flat crest and usually they do not present any slip face (McKee, 1966).

#### 1.2. Aim of the thesis

The overall aim of this study is to decipher a new archive of temporal wind-field variations recorded in the sedimentary succession of a migrating coastal dune. The study focuses on the following objectives:

 A geochronological frame is an essential tool in order to interpret past climatic changes more accurately. Therefore, the first objective is to develop an age model combining optically stimulated luminescence (OSL) dating and aerial images.

- The second objective is to study the development of the dune in time. For this purpose, the internal architecture of the dune is revealed by using a GPR, whereas the dune geomorphology is reconstructed using aerial images.

- Finally, once the time frame is established and the process of the dune development is understood, a mathematical function is defined in order to describe the correlation between a sedimentological record and a meteorological record. This process will allow us to reconstruct

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wind-field variations in absence of instrumental data.

## 1.3. Outline of the thesis

This thesis is subdivided into five chapters. Chapter 1 is the introduction, Chapter 2 deals with the development of an age model combining OSL dating and a series of aerial images and cartographic maps dating back to 1925. It has been published as: Costas, I. et al., Comparison of OSL ages from young dune sediments with a high-resolution independent age model, Quaternary Geochronology (2012), 10, 16-23. Chapter 3 focuses on the development over time of the dune and consequently presents the internal as well as the external changes that the dune has experienced during its migration. In Chapter 4 the sedimentological record is compared to the instrumental record in order to find a function describing their correlation allowing us to reconstruct the wind-field variations in absence of data. Chapter 5 summarizes the main conclusions of the previous chapters and gives an outlook for further research.

## Chapter 2

# Comparison of OSL ages from young dune sediments with a high-resolution independent age model

## Abstract

In order to test the accuracy of quartz optically stimulated luminescence (OSL) dating for young dune sediments (<100 yr), a series of aerial images of a migrating sand dune is used to cross validate OSL ages. The investigated dune is situated on the northern part of the island of Sylt (southern North Sea). Based on aerial images and a map from 1925 to 2009 and the internal architecture of the dune obtained by ground penetrating radar (GPR), an independent age model was developed to attribute sedimentary-architectural elements of the dune to time. The annual rate of dune migration is calculated to be around 4.1 m/yr. Along a 245 m transect oriented parallel to the direction of dune movement, 13 samples for OSL dating were collected at equidistant locations. Sand-sized quartz (150-250 µm) was used for determining the equivalent dose (D<sub>a</sub>) applying a single-aliquot regenerative-dose (SAR) protocol. Results show that the oldest OSL age from the investigated recent dune appeared to be 110±10 yr, whereas the modern analogue was dated to 34±3 yr. In comparison with the aerial images, the OSL ages show a systematic overestimation of 10-40 yr for six out of seven younger samples, which are expected to be younger than ~60 yr. This offset is negligible for older samples, but a substantial error in these younger ages. The overestimation is originated from a combination of small thermal transfer of 4-12 mGy during preheat and incomplete bleaching in the medium OSL component causing a residual dose of about 15 mGy. The contribution of the incompletely bleached medium component cannot be removed totally by an early background subtraction approach. Despite the observed offset for youngest samples, this study corroborates the suitability of the OSL technique to date young dune sediments (<100 yr).

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#### 2.1. Introduction

Optically stimulated luminescence (OSL) dating has proved to be a powerful technique to determine depositional ages of coastal aeolian sediments around the world (Clemmensen et al., 2001c; Murray-Wallace et al., 2002; Ballarini et al., 2003; Madsen et al., 2007; Alappat et al., 2011; Reimann et al., 2011). Quartz OSL dating studies based on the SAR protocol applied to date very young sediments (<100 yr) have provided reliable results (Murray and Olley, 2002; Ballarini et al., 2003; Madsen et al., 2003; Madsen et al., 2007). However, the application of quartz OSL dating to very young sediments is still challenging. This challenge is due to a low signal-to-noise ratio of the natural OSL signal, thermal transfer, and small residuals caused by an insufficient resetting of the luminescence signal (Madsen and Murray, 2009). Thus, attention should be paid when dealing with very young samples.

Coastal dunes are important palaeoclimatic archives that hold records of general climate shifts and sea-level fluctuations (e.g. Clemmensen et al., 2001a; Wilson et al., 2004; Aagaard et al., 2007). Development and migration of coastal dunes are affected by availability of sediment, vegetation cover and precipitation, and wind strength and direction. Therefore, dunes can provide an important record of wind-field variations (e.g. McKee, 1979; Lancaster, 1990; Jewell and Nicoll, 2011). An accurate and precise geochronological framework in the highest possible chronological resolution is essential to make migrating dunes available as an archive of temporal wind-field variations. The objective of this paper is to assess the accuracy and reliability of quartz OSL to date very young dune sediments (<100 yr) by comparing it with a high resolution independent age control based on a series of aerial images dating back to 1925.

#### 2.2. Study area and independent age control

The study area is situated on the northern part of the island of Sylt, a barrier island in the southern North Sea (Fig. 2.1). The island consists of a core of Saalian and Elesterian moraines as well as Tertiary sediments (Gripp and Becker, 1940). Attached to the moraine core to the north and to the south, there are two Holocene barrier spits, forming an elongated island of 38 km long. Aeolian sand dunes form the youngest sedimentary unit of northern Sylt. This system was first investigated by Priesmeier (1970) following a geomorphological approach. He assumed that the growth and migration of the dune were cyclic: a new generation of sand dunes accumulates every 300 years along the western coast and starts migrating eastward. Based on aerial images, he calculated that after 900 to 1000 AD the dunes traversed the

northern spit and reached the tidal bay on the leeward side of the island. At present, the surface of the island is characterized by stabilized and active dunes, which have a maximum height of 35 m, and broad interdune slacks, which are mostly deflated down to the ground



**Figure 2.1.** Map of the study area. **A:** Simplified map of northern Europe and the North Sea. **B:** Digital elevation model from northern Sylt obtained with the airbone Lidar (data provided by Amt für ländliche Räume, Husum). **C:** Aerial image of the dune under study. The dashed lines represent the GPR profiles collected and the straight line indicates the profile where the OSL samples were collected.





water table. Westerly winds between 225° and 315° are dominant and the average wind speed is around 7 m/s. The studied dune is NNE-SSW oriented, approximately 900 m long, and 400 to 500 m wide. It is situated 900 m from the western coast. The annual rate of dune movement is around 4.1 m/a.

Aerial images were used as independent age control (Ludwig, 2010). Seven aerial images as well as one historical map are available for northern Sylt. The map dates back to 1925 (Priesmeier, 1970), whereas aerial images were taken in 1936, 1944, 1958, 1965, 1988, 1998, 2003, and 2009. After georeferencing the images, the toe of the dune along the lee side was digitized (Fig. 2.2A). These points were projected into the GPR profiles and drawn following the dune foresets to obtain the isochrones (Fig. 2.2B).



**Figure 2.3.** Summary of the OSL ages using the LBG (white circles), the EBG (black circles) and compared to the independent age estimates (triangles). The OSL ages are based on the calculated mean De. The independent estimates were fitted with a straight line. The black error bars indicate the 1-sigma standard error, whereas the grey error bars indicate the 2-sigma error.

The position of each isochrone has an accuracy of  $\pm$  1-2 m, except the map which has a lower accuracy. This uncertainty of the isochrones ( $\pm$  1-2 m) is smaller than the annual migration rate; therefore the temporal precision is better than one year. The eight isochrones were plotted against the distance from the foot of the luv and fitted with a straight line. The fitted line, extrapolated to the starting point, indicates that the transect covers the time span since 1912 AD and thus, provides a high-resolution sedimentary record (Fig. 2.3).

#### 2.3. Methods

#### 2.3.1. Sampling and preparation

Sampling was carried out along a 245 m long transect oriented parallel to the dune movement (W-E). The transect starts at the foot of the luv side and ends at the crest of the dune (Fig. 2.2). Additionally, a ground-penetrating radar (GPR) profile was collected to allow for a stratigraphic control of sample position. Thirteen samples for OSL dating were taken at equidistant locations at a depth of 0.7 m below the surface (Fig. 2.2). Opaque tubes inserted horizontally into the sediment were used for sampling and subsequently sealed to avoid light exposure of the luminescence samples. Additionally, samples for dose rate determination were taken from the surroundings of each sampling point. The expected ages for each OSL sample were calculated from the fitted line (Fig. 2.3) and are listed in Table 2.1. Sample recovery and processing were carried out in 2010.

The tubes were opened under subdued red light conditions. About two centimetres from both ends of the tube were discarded due to a possible light exposure. The rest of the sample was dried at 50°C for one day. The grain-size fraction 150 to 250  $\mu$ m was separated by drysieving. This fraction was treated with HCl to dissolve carbonates, with Na<sub>2</sub>C<sub>2</sub>O<sub>4</sub>, to dissolve aggregates, and with H<sub>2</sub>O<sub>2</sub> to remove organic matter. The quartz minerals were extracted using a heavy-liquid solution (sodium polytungstate). Finally, 10 g of quartz grains were etched for 1 hour with concentrated HF. This last step is necessary to dissolve feldspar and to etch the outer (i.e. alpha-irradiated) surface of quartz grains.

#### 2.3.2. Dose rate determination

The radionuclide concentration of the sediment surrounding was determined by high-resolution gamma spectroscopy using 700 g of sediment filled in Marinelli beakers.

				D h Im Oul	D h Im Cul	CAM <sup>o</sup> D	MAM <sup>d</sup> D	001	001
Field ID	n [aliquots]	Expected age <sup>a</sup> [yr]	Expected D <sub>e</sub> <sup>a</sup> [mGy]	(with LBG)	(with EBG)	[mGy] <sup>°</sup> (with EBG)	[mGy] <sup>°</sup> (with EBG)	USL age [yr] (with LBG)	[yr] (with EBG)
GWD-0	23	98±10	73±7	135±8	119±7	116±6	101±9	180±20	160±20
GWD-10	24	94±9	56±6	68±5	52±3	55±3	52±6	115±13	89±9
GWD-20	24	90±9	55±5	83±5	65±3		62±6	140±15	110±10
GWD-40	23	82±8	54±5	77±4	56±3		55±6	117±11	86±8
GWD-60	23	75±7	53±5	84±5	70±4	71±4	67±7	118±11	98±9
GWD-80	24	67±7	50±5	70±7	55±5	54±5	48±4	93±11	72±8
GWD- 100	24	59±6	41±4	86±6	66±5	68±5	64±8	120±13	94±10
GWD- 140	24	43±4	31±3	54±4	46±5	49±5	42±8	76±8	65±9
GWD- 160	24	35±4	26±3	81±4	71±4	71±4	68±7	110±10	97±9
GWD- 180	24	28±3	19±2	65±4	51±3	51±3	49±6	97±9	77±7
GWD- 200	23	20±2	13±1	52±6	41±4	42±3	38±7	77±10	60±8
GWD- 220	24	12±1	8±1	42±3	28±3	34±4	28±7	60±7	40±5
GWD- 245	23	2±1	1±1	31±5	23±5		20±8	47±8	34±3

Table 2.1. Dating results.

<sup>a</sup> Expected ages and De estimated from the independent age control based on aerial images.

<sup>b</sup> Equivalent doses based on the average mean with 1-sigma standard error.

<sup>c</sup> Equivalent doses calculated based on the Central Age Model (Galbraith et al., 1999).

<sup>d</sup> Equivalent doses calculated based on the Minimum Age Model (Galbraith et al., 1999).

Before the measurements, the beakers were stored for a minimum of four weeks to adjust the radon disequilibrium. The activity of <sup>238</sup>U-series and <sup>232</sup>Th-series nuclides and that of <sup>40</sup>K were converted into dose rates using the factors provided by Adamiec and Aitken (1998). The water content was assumed to be  $6\pm3$  %. This value is in agreement with water contents estimated for sediments from other studies from European coastal dunes (Ballarini et al., 2003; Madsen et al., 2007). The beta-attenuation and the effect of moisture were calculated according to Mejdahl (1979) and Aitken (1985), respectively. The contribution of the cosmic rays was calculated according to Prescott and Stephan (1982) Prescott and Hutton (1994) based on the latitude and the altitude of the sampling sites and the burial depth of the samples.

#### 2.3.3.OSL measurements

An automated Risø reader TL/OSL DA-15 was used for OSL measurements. The samples were stimulated with blue light-emitting diodes (LEDs) at 470 nm with a power at the sample position of 32 mWcm<sup>-2</sup>. A 7.5 mm Hoya U-340 was used as detection filter (Bøtter-Jensen et al., 2000). The quartz samples were settled on stainless steel discs with different sizes: small aliquots containing ~60-80 grains, medium aliquots containing ~300 grains, and large aliquots containing ~800 grains. The pretest and final D measurements were made on medium size aliquots. The single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000) was used for D<sub>a</sub> determination. Recycling ratios and IR/OSL depletion ratios (Duller, 2003) were calculated to asses the effectiveness of the sensitivity change correction (Wintle and Murray, 2006) and to check feldspar contamination, respectively. Aliquots with recycling ratios and/or IR/OSL depletion ratios of >15 % from unity were excluded from D<sub>e</sub> calculation. The regenerative dose points were fitted by a linear function to obtain the SAR dose-response curve. To determine the D<sub>e</sub>, it was assumed that the dose-response curve passes through the origin. The selection of an appropriate thermal treatment was based on the pretests carried out by Reimann et al. (2012) who analysed aeolian sand sheets from the study area. They obtained a preheat plateau between 160-260 °C but thermal transfer was significantly increased for preheat temperatures >220 °C. A preheat temperature of 180 °C and a cutheat temperature of 160°C prior to the OSL measurements were applied to reduce thermal transfer to a negligible level, which is a very important issue when dating young samples (Madsen and Murray, 2009). These conditions are similar to those used by Ballarini et al. (2003) and Madsen et al. (2007) who successfully dated very young (<100 yr) coastal aeolian sediments from the Netherlands and Denmark.

The net OSL signal was calculated from the first 0.48 s of the OSL decay curve. Two different integration intervals were used for background subtraction: a late background subtraction (LBG), with an integration interval between 32 and 40 s, and an early background subtraction (EBG), which utilise an integration interval between 0.48 and 1.92 s. Cunningham and Wallinga (2010) recommend the use of the EBG approach especially for young sediments, because it minimises the less suitable slow and medium signal component of the OSL signal, show less recuperation, less thermal transfer, and tighter D<sub>e</sub> distributions. Prior to the D<sub>e</sub> measurements, dose recovery experiments on six medium aliquots of each sample were carried out to test the suitability of the applied SAR and thermal treatment (Wintle and Murray, 2006). The dose recovery ratios were calculated using both EBG and LBG approaches described above.

#### 2.4. Results

The  $D_e$  values, the dose rate, and the radionuclide concentrations for the thirteen samples were determined for age calculation. The total dose rate for the samples is relatively low due to a low concentration of potassium (0.31 to 0.49%) and ranges between 0.591±0.052 mGy/yr (GWD-10) and 0.755±0.052 mGy/yr (GWD-80) (Table 2.2).

Field ID	Grain size [µm]	K (%)	Th (ppm)	U (ppm)	Cosmic dose rate <sup>a</sup> [mGy/yr]	Sediment dose rate <sup>b</sup> [mGy/yr]	Total dose rate <sup>c</sup> [mGy/yr]
GWD-0	150-200	0.460±0.010	1.150±0.020	0.390±0.010	0.190±0.019	0.558±0.048	0.748±0.052
GWD-10	150-250	0.310±0.010	1.090±0.010	0.320±0.010	0.190±0.019	0.402±0.048	0.591±0.052
GWD-20	200-250	0.350±0.010	0.900±0.010	0.280±0.010	0.190±0.019	0.416±0.048	0.606±0.052
GWD-40	200-250	0.410±0.010	0.880±0.010	0.270±0.010	0.190±0.019	$0.467 \pm 0.048$	0.657±0.052
GWD-60	200-250	0.460±0.010	0.950±0.020	0.310±0.010	0.190±0.019	0.523±0.048	0.713±0.052
GWD-80	200-250	0.490±0.010	1.080±0.020	0.350±0.010	0.190±0.019	0.565±0.049	0.755±0.052
GWD-100	200-250	0.410±0.010	1.360±0.020	0.360±0.010	0.190±0.019	0.511±0.048	0.701±0.052
GWD-120	150-250	0.390±0.010	1.560±0.020	0.440±0.010	0.190±0.019	0.523±0.049	0.713±0.052
GWD-160	200-250	0.400±0.010	1.740±0.040	0.450±0.010	0.190±0.019	0.540±0.048	0.730±0.052
GWD-180	200-250	0.390±0.010	1.200±0.020	0.340±0.010	0.190±0.019	0.480±0.048	0.670±0.052
GWD-200	200-250	0.330±0.010	1.830±0.020	0.450±0.010	0.190±0.019	0.482±0.048	0.672±0.052
GWD-220	150-200	0.360±0.010	1.750±0.020	0.450±0.010	0.190±0.019	0.512±0.048	0.702±0.052
GWD-245	200-250	0.34±0.010	1.540±0.020	0.420±0.010	0.190±0.019	0.469±0.048	0.659±0.052

Table 2.2. Results of dose rate determination

<sup>a</sup> Cosmic dose rate obtained after Prescott and Hutton (1994) and Prescott and Stephan (1982).

<sup>b</sup> Sediment dose rate obtained after using the conversion factors of Adamiec and Aitken (1998) for Uranium, Thorium and Potassium, beta-dose attenuation according to Mejdahl (1979) and water-content attenuation according to Aitken (1985).

<sup>c</sup> Total dose rate obtained after Aitken (1985).

The measured/given dose ratios obtained during the dose recovery experiment were in the acceptable range (between 0.9-1.1) according to (Wintle and Murray, 2006). An average ratio of  $1.019\pm0.004$  (n = 78) and  $1.011\pm0.007$  (n = 78) using the LBG and the EBG, respectively were obtained for the 13 samples (Fig. 2.4).

For each sample, the  $D_e$  distributions of 24 medium aliquots were used for  $D_e$  determination. Arnold et al. (2007) proposed the use of the Central Age Model (CAM) of Galbraith et al. (1999) for well-bleached sediments such as aeolian sediments. However, for some of the studied samples an overdispersion of zero was obtained and accordingly no CAM  $D_e$  could be calculated for these samples. Therefore, the OSL ages were calculated based on the mean  $D_e$  and the 1-sigma standard error. For the samples having both CAM and mean  $D_e$  the results agree within uncertainties (Table 2.1). The  $D_e$  values obtained from the EBG approach are ranged from 119±7 mGy for the oldest sample (GWD-0) to 23±5 mGy for the modern analogue (GWD-245); the latter was taken from the modern dune crest. There is a general decrease of the  $D_e$  with the increase of the distance from the foot of the luv side of the dune to crest, thus the OSL ages are stratigraphically consistent within 2- $\sigma$  uncertainties (Fig. 2.3 and Table 2.1). The oldest age appeared to be 160 ± 20 yr, whereas the modern analogue was dated to 34 ± 3 yr using EBG. Using the LBG, the oldest age is 180 ± 20 yr, and the youngest age is 47 ± 8 yr.



**Figure 2.4.** Dose recovery distributions including six aliquots per sample for the LBG (a) and for the EBG (b) are shown. Preheat temperature was 180 °C and cut-heat was 160 °C. The dotted lines represent the range of acceptability (0.9 to 1.1, according to Wintle and Murray, 2006). This figure is not included on the printed version of this manuscript. It can be found in the digital version as supplementary material. http://dx.doi.org/10.1016/j. quageo.2012.03.007

#### 2.5. Discussion

Results of the dose recovery test indicate that the SAR protocol is suitable for the samples (Fig. 2.4). Considering the independent age control, it calculated that sample GWD-0 was deposited in 1912 (98 yr). However, GPR data show that this sample was taken directly from the sedimentary boundary between the active dune and the underlying sediment. The much older age (160  $\pm$  20 yr by the EBG) obtained from this sample suggests that it was likely deposited by a previous dune. Therefore this sample is excluded from the discussion here. The ages obtained from the LBG were always older than those from the EBG (Table 2.1). The LBG subtraction leads to an overestimation of 20-60 years for all the samples, although samples GWD-10 and GWD-80 agree within the 2-sigma error with the expected D<sub>e</sub>. These expected D<sub>e</sub>s (Table 2.1) were calculated by multiplying the expected ages by the dose rate for each sample. The calculation of the OSL ages using the EBG subtraction solves the age overestimation problem for the oldest 5 samples (GWD-10, -20, -40, -60, and -80, Fig. 2.3): samples GWD-20, GWD-40 and GWD-80 have D<sub>e</sub> values in agreement within 1-sigma

uncertainties with the expected  $D_e$  values whereas samples, GWD-10 and GWD-60 agree within 2-sigma uncertainties (Table 2.1). According to Cunningham and Wallinga (2010) the reduction in  $D_e$  compared with the LBG subtraction is due to the reduction in thermal transfer and/or smaller contributions from unsuitable OSL signal components (i.e. medium or slow components) with higher probability of incomplete signal resetting. The results support the benefit of the EBG approach proposed by Cunningham and Wallinga (2010) for our young samples.

However, despite using the EBG an overestimation between 10 to 40 years remains for the 7 youngest samples (GWD-100, -140, -160, -180, -200, -220 and -245, Fig. 2.3) even though sample GWD-140 agrees within 2-sigma uncertainties with the expected age. The other six youngest samples are significantly overestimated considering the 2-sigma confidence interval. In contrast, Ballarini et al. (2003) and Madsen et al. (2007) successfully dated very young coastal sediments by using the SAR measurement protocol with the same thermal treatment. Both papers reported reliable OSL ages from samples from coastal dunes and beach ridges from the North Sea in similar age range. They obtained ages of  $6 \pm 2$  and  $10 \pm 3$  years for their youngest samples from the Dutch and Danish coast, respectively.

Four possible causes of the age overestimation are considered and discussed: 1) a dose rate variation in the burial time; 2) thermal transfer of charge by heating during the measurements; 3) the effect of low signal-to-noise ratio, and 4) incomplete resetting of the OSL signal before burial. First, the effect of disregarded dose rate variations on the ages is discussed. The main factors that could possibly affect dose rate determination are variations in the water content or changes of the overburden through time. The dose rate effect of disequilibria in the uranium decay chain is assumed to be insignificant because the deviation of the estimated dose rate from the true dose rate is usually smaller than 3% (Olley et al., 1996). Water content is a factor that can significantly modify the resultant value of the dose rate, since water can absorb radiation. Water content might has been slightly higher in the past, especially for the first three samples (GWD-0 to GWD-20) which are relatively close to the ground-water table. At present, the ground-water table in the studied area is situated at approximately 1.8 m msl and the oldest sample GWD-0 is situated at 3 m msl. The ground-water table in the study area is hydrodynamically controlled by the sea-level (Lindhorst et al., 2008) and variations of 1.2 m are unlikely during the last 150 years. However, higher water content reduces the dose rate and therefore it cannot be a cause of age overestimation.

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The thickness of the overburden is one of the factors that possibly affect the cosmic-dose contribution to the overall dose rate. Changes of the sediment cover through time, for example due to the migration of the dune, should be taken into account when estimating correct cosmic-doses. However, the oldest samples are potentially more affected by this factor because its importance increases with burial time. Therefore, it is very unlikely that the variation in the thickness of the overburden is responsible for the overestimation observed in the youngest samples.

Thermal transfer, incomplete bleaching, low signal-to-noise ratio or difficulty in counting very dim natural OSL signal are the most common problems within  $D_e$  determination that can lead to an overestimation in very young samples (Madsen and Murray, 2009). Therefore, after the first measurements, it was decided to carry out some additional experiments on samples GWD-80, GWD-140, and GWD-245. These samples have very precise independent age estimates due to the excellent matching between the positions for the past dune toe obtained from aerial images and those of the OSL samples. To check and quantify thermal transfer, additional thermal transfer tests (i.e. the aliquots were bleached for 2 times for 40 s prior to  $D_e$  measurements by using the blue LEDs in the reader) at 140, 160 and 180°C (four discs for each temperature) were carried out on the 3 samples.



**Figure 2.5.** Residual De of sample GWD-80, GWD-140, and GWD-245 at 160 (black dots) and 180°C (white dots) after bleaching by blue LEDs in the reader. The errors represent 1-sigma standard errors. The signals were evaluated using the EBG (x-axis) and the LBG (y-axis).

Results for preheat temperatures at 140°C and 160°C are indistinguishable and consistent with zero. However, a preheat of 180°C induces a small thermal transfer of 8-20 mGy for LBG and 4-12 mGy for the EBG (Fig. 2.5). This observation clearly demonstrates the beneficial effects of the EBG approach proposed by Cunningham and Wallinga (2010). Therefore the  $D_e$  values for these samples were re-measured applying a lower preheat temperature of 160°C. The results obtained were 56 ± 2, 50 ± 2, and 18 ± 2 mGy for samples GWD-80, GWD-140, and GWD-245, respectively. These results do not show a significant reduction in the mean  $D_e$  values compared to the results obtained at 180°C (see Table 2.1). However, the difference between the thermal transfer obtained from 160°C and 180°C preheats are 6, 2, and 13 mGy for GWD-80, GWD-140 and GWD-245, thus the small difference in the thermal transfer effects was probably masked by the error range of the  $D_e$  values.

Finally, in order to examine the effect of low signal-to-noise ratio and incomplete resetting, the 3 samples were re-measured using different aliquot sizes. By measuring large aliquots (~800 grains) the effect of too low signal-to-noise ratio can be investigated because the number of light emitting grains is increased. Whereas that by measuring small aliquots (~60-80 grains) can be tested if there is an averaging effect due to the presence of some high D<sub>e</sub> grains. The presence of high D<sub>e</sub> grains masks the very low D<sub>e</sub> grains (with zero and negative values) because there are only very few light emitting grains (approximately 1-3) on the small aliquot (Reimann et al., 2012). Results for the three aliquot sizes indicate that D<sub>e</sub> is independent of the measured aliquot size for our samples (Fig. 2.6). For sample GWD-80 the obtained mean D<sub>e</sub> values agree within 1-sigma uncertainties with the expected D<sub>e</sub> (Fig. 2.6). However, for sample GWD-140 and sample GWD-245 none of the obtained D<sub>e</sub> values with the different aliquots sizes agree within 2-sigma uncertainties with the expected De.

Furthermore, the Minimum Age Model (MAM) (Galbraith et al., 1999) was tested to identify potential minimum (well-bleached)  $D_e$  populations within the small aliquot distributions. Within MAM calculations an overdispersion of 0.1 was assumed for a well-bleached  $D_e$  population within a small aliquot  $D_e$  distribution (Rodnight et al., 2006). The MAM  $D_e$  values are indistinguishable from the EBG mean  $D_e$  values (Table 2.1). Moreover, the MAM results could not detect distinct minimum dose population of well-bleached grains. This indicates that the bleaching prior to the deposition was uniform, not heterogeneous.

In order to evaluate if all OSL signal components were well zeroed prior to the deposition, 24 aliquots from the modern analogue (GWD-245) were bleached in daylight for one week.



**Figure 2.6.** De distributions of sample GWD-80 (A), GWD-140 (B), and GWD-245 (C) are shown considering the different aliquots sizes (large, LA; medium, MA; and small, SA). The dotted lines represent the expected De, whereas the shadowed area the measured mean De and the standard error on the mean.

Afterwards, these aliquots were measured using a preheat at 180°C. The bleached aliquots gave a residual  $D_e$  of 11 ± 2 mGy for the LBG and of 8 ± 1 mGy for the EBG, which is presumably due to a thermal transfer (very similar to the results obtained for the thermal transfer test). However, considering the EBG  $D_e$  of 23 ± 5 mGy at 180°C for the natural  $D_e$  of GWD-245, there is a remaining bleachable residual dose of about 15 mGy that cannot be attributed to

the thermal transfer. Furthermore, the bleaching of the OSL signal was found to be uniform since no minimum D populations were detected within the small aliquot D distributions of our samples. However, it is possible that this remaining bleachable residual dose originates from a contribution of a slower bleaching component of the OSL signal which was not completely zeroed prior to the natural aeolian deposition despite this signal was zeroed within one week daylight exposure. To examine this possibility, a natural and a regenerated OSL signals from GWD-140 were fitted into 3 exponentially decaying components plus a constant. The first 2 components are correlated to fast and medium components by Jain et al. (2003) and Singarayer and Bailey (2003), according to their photoionisation cross sections,  $2.24 \pm 0.10$ x 10<sup>-17</sup> cm<sup>-2</sup> and 6.58  $\pm$  0.82 x 10<sup>-18</sup> cm<sup>-2</sup>, respectively. The component analysis indicates that the initial part of the natural OSL signal is dominated by the medium component, whereas the regenerated decay curve is dominated by the fast component (Fig. 2.7). The contribution of dominant medium component cannot be removed by the EBG approach, and this probably causes a residual dose of ~15 mGy due to homogenous incomplete bleaching for our samples. The homogenous incomplete bleaching also explains why the D values are very similar for the different aliquot sizes and, in particular, why no minimum D<sub>e</sub> populations were found in the small aliquot D distributions. The residual dose in the modern analogue of ~15 mGy is equivalent to an age of ~20-25 yr (depending on the dose rate of the sample) and thus is able to account for the observed age overestimation in our youngest samples (GWD-100 to GWD-245).



**Figure 2.7.** OSL component analysis using an aliquot of GWD-140 for (A) natural and (B) regenerated OSL decay curves.

#### 2.6. Conclusions

In this paper the performance of quartz OSL to date very young (< 100 yr) dune samples from the southern North Sea coast is tested. The main conclusions are:

• This study favours the benefit of the EBG approach of Cunningham and Wallinga (2010) compared to the conventional LBG for sediments of the recent past. Most EBG ages agreed with the independent age control and thermal transfer is significantly reduced (see Fig. 2.3 and 2.5).

• The overestimation occurred in the youngest samples is attributed to a small thermal transfer of 4-12 mGy and incomplete bleaching in the medium OSL component which has a significant effect on very young samples with low natural OSL signals. This kind of incomplete bleaching can neither be removed by EBG nor be observed in small aliquot D<sub>e</sub> distributions as discrete minimum D<sub>e</sub> population. However, the use of a modern analogue approach is recommended in order to quantify the resulting residual dose. For our modern analogue a residual dose of ~15 mGy (equivalent to 20-25 yr) was caused by incomplete bleaching of the medium OSL component. In cases where no independent age control is available this residual dose can be used to correct the OSL age estimates of very young samples.

• Comparison of the OSL chronology to expected age estimates based on the independent age model demonstrates the suitability of the OSL technique to evaluate the accuracy and reliability of OSL to date very young dune sediments in a high resolution. The EBG OSL ages of 5 samples from the oldest part of the dune are accurate and the reliability is confirmed by independent age estimates. However, the EBG ages of 6 samples from the youngest part are systematically overestimated for 10-40 yr (i.e. around 20 mGy). The relative uncertainty of the ages is in the order of ~10 %.

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## **Chapter 3**

## Evolution of a migrating dune

## Abstract

Migrating dunes are dynamic systems, which can be easily influenced by changes on external factors such as vegetation cover, sediment supply, precipitation, and wind strength and direction. These changes will be reflected in the geomorphology as well as in the internal architecture of the dune. Aerial images were used to investigate the geomorphological development of a migrating dune located in the northern part of Sylt Island (southern North Sea) over the last 73 years. These aerial images also allowed to establish a chronostratigraphy of the investigated dune and to estimate its migration velocity. Additionally, the internal architecture of the dune was revealed using a 200 MHz ground-penetrating radar (GPR).

Data showed that during its eastward migration, the dune developed from a transverse to a parabolic dune. This transformation, which occurred between 1958 and 1965, was caused by a decrease on the sediment supply and an increase on the vegetation cover. After 1965, the internal architecture shows a profound change of forest geometry from tabular to convex, reflecting the geomorphological change. Additionally, sedimentary architectural elements, such erosional unconformities or toplap geometries were related to specific wind characteristics. Erosional unconformities developed only until the early 1940's, reflecting that this was a period with strong easterly storms. This fact was also confirmed by analysing wind data of a meteorological station situated near the evaluated dune. Toplap geometries were identified by correlating with periods of high wind-direction variability.

The migration velocities, calculated based on the aerial images, showed that the migration velocity of the dune increased over time. This increase was associated to the reduction of the dune surface. However, other factors should be taken into account when analysing the variations of the migration velocities during the time intervals defined by the aerial images, such as the annual number of days with winds higher than 3 Bft and the annual precipitation.

#### 3.1. Introduction

The knowledge of the internal architecture of sand dunes is essential for characterising dune growth and dune morphodynamics, both at the present and in the geologic past (Neal and Roberts, 2001; Hugenholtz et al., 2007; Gomez-Ortiz et al., 2009). Despite the importance of understanding the internal structures of dunes, non-significant attention has been paid to the internal structures of modern dunes in comparison to ancient aeolian sand bodies due to the difficulties of obtaining suitable sections in dry and unlithified dune sands (Pye and Tsoar, 2009). In the past, investigating the internal structures of dunes was a complex procedure, which was limited to excavating shallow trenches. Consequently, this had caused a high environmental impact (e.g. McKee, 1966; Bigarella et al., 1969; Mckee et al., 1971; Halsev et al., 1990). Due to the difficulty of this process, the research was limited to dunes lower than 10 m or observations of field exposures (McKee, 1966). However, since the mid-1990s, the ground-penetrating radar (GPR) has become a widely used tool in aeolian investigations (Bristow et al., 1996; Clemmensen et al., 1996, 2001a; Harari, 1996; Bailey and Bristow, 2000; McGourty and Wilson, 2000; Neal and Roberts, 2001; van Dam et al., 2002, 2003). The success of this tool relies on the fact that it is a non-intrusive tool, it is cost and time effective, and it allows the visualization of the internal dune stratigraphy with a centimetre to decimetre scale. Such detailed information about dune architecture was not possible to obtain before the development of this technique.

Aeolian dunes are quite sensitive to environmental changes; therefore, any changes affecting the dune will be recorded in its stratigraphy and in its geomorphology. Dune development is a complex process that is highly influenced by variations on sediment type and availability, wind strength and direction, and humidity and vegetation cover (Anthonsen et al., 1996; Labuz, 2004; Girardi and Davis, 2010). Changes to any of these factors will cause modifications to the existing dune (Pye and Tsoar, 2009). Thus, each kind of dune morphology will record a unique pattern of growth (McKee, 1979). Orientation, thickness, and form of stratification depend greatly on the dune form which, in turn, reflects the wind regime and the importance of vegetation during dune development (Pye, 1983). The aim of this study is to integrate the GPR technique, aerial images, and meteorological data to investigate the internal stratigraphy, as well as the geomorphological development of a migrating dune in order to understand the factors that have determined the dune's evolution. Understanding these factors, which affect the dune form and stratigraphy, will allow us to assess past and future behaviour of dunes due to environmental changes (Wolfe, 1997; David et al., 1999; Hugenholtz et al., 2007).

## 3.2. Geological setting

The research area is located in the northern part of the island of Sylt in the southern North Sea. Sylt belongs to the North-Frisian Islands and it is situated 15 km off the German North Sea coast, close to the Denmark border (Fig. 3.1A). The island is formed by a moraine core (Fig. 3.1B) as well as by re-worked tertiary sediments (Gripp and Becker, 1940). During the late Holocene, two large sandy spit systems developed north and south of the moraine core, forming an elongated island of 38 kilometres long (Gripp and Simon, 1940). Westerly winds between 225° and 315° prevail and the mean wind velocity is approximately of 7 m/s.

The northern spit, which is characterised by fixed and active dunes and broad interdune slacks, constitutes the youngest sedimentary unit. The dune growth and its migration are cyclic: every 300 years, a new generation of sand dunes accumulates at the western coast and starts migrating landward (Priesmeier, 1970). Figure 3.1C shows a terrain model with the three generations of dunes extended currently on northern Sylt. The vegetation present on the interdune area consists of Impetrum nigrum, Pyrola rotundifolia, and Oxycoccus macrocarpon, whereas on the dunes the predominant vegetation is Ammophilia arenaria and Elymus arenaria. Ammophilia arenaria is the best indicator for sand burial (Levin et al., 2008).

The investigated dune was elected for being the biggest dune in the area, with dimensions of up to 35 m height, 900 m long, and 400-500 m wide, as well as for being the most active dune in the area. It is oriented NNE-SSW and situated about 900 m far from the western coast.

## 3.3. Methods

## 3.3.1. Ground-penetrating radar (GPR)

The stratigraphic architecture of the studied dune was investigated by means of a groundpenetrating radar (GPR). The GPR is a non-invasive method used to investigate the shallow subsurface with a decimetre resolution. It is based on the transmission of high-frequency electromagnetic pulses, which are reflected at electromagnetic discontinuities (Neal, 2004). Electromagnetic discontinuities are caused by e.g. changes in sediment water content, porosity, lithology, grain shape, and grain orientation. Previous studies have shown that there is a direct relationship between primary radar reflections and primary bedding (Neal and Roberts, 2001; van Dam, 2001; Neal, 2004).



**Figure 3.1:** Study area modified after Lindhorst et al. 2010. **A:** Sketch of the southern North Sea with the location of Sylt Island (black circle). **B:** Simplified geological map of Sylt (after Dietz & Heck, 1952). **C:** Terrain model of northern Sylt obtained by airborne LIDAR (data provided by Amt für ländliche Räume, Husum). Three different generations of dunes can be observed. The investigated dune is marked with a black box. The present location of the meteorological station used is indicated by the red dot.

Consequently, features such as sedimentary structures, lithological boundaries and the water table are detected.

The GPR survey was performed using a Geophysical Survey Systems Inc. radar system SIR-3000 with a 200 MHz antenna. This frequency presents the best agreement between

penetration depth and resolution in the study area (Lindhorst, 2007). Radar data were collected in a continuous mode with a survey wheel as distance trigger. During the acquisition of the data, a trace increment (space in-between shot points) of 5 cm was used and 2048 samples were collected for each trace. According to the manufacturer settings neither frequency filtering nor stacking were applied during data collection.

Data processing, including time-zero offset, frequency bandpass filtering, background removal, gain adjustment, and migration, was done to enhance the signal-to-noise ratio using ReflexW (Sandmeier, v.6.0, 2008). Based on the fitting diffraction hyperbolas an average subsurface velocity of 0.13 m/ns was estimated, which is a common value for dry sands (Jol and Bristow, 2003). Correction for topography was also applied to restore different terrain altitudes and to deskew subsurface geometries. The data necessary for the topographic correction were obtained with a differential global-positioning system (Ashtech ProMark II). The penetration depth achieved reached up to approximately 30 m and had a vertical resolution of 16.25 cm. In total, 18 GPR profiles were collected in both parallel and perpendicular directions to the depositional dip to visualize the architecture of the dune.

Interpretation of the GPR data was done based on the terminology proposed by Neal (2004) following the principles of seismic stratigraphy. This is based on the terminology used to define radar surfaces and radar facies following the terminology summarized by Neal (2004), and modified after Campbell (1967), Mitchum et al. (1977) and Allen (1982), which consists of identifying reflection terminations.

#### 3.3.2. Age model

Dune morphological changes as well as migration rates were reconstructed from a series of historical aerial images. The aerial images are available for the following years: 1936, 1944, 1958, 1965, 1988, 1998, 2003, and 2009. They were processed and georeferenced with the ArcGIS software (ESRI, 2008). The position of the dune was tracked by digitizing the toe of the dune in the aerial images. Afterwards, these points were projected into the GPR profiles to depict the position of the toe of the dune. The location of each timeline has an accuracy of  $\pm$  1-2 m. A more detailed description of the construction of the age model can be found in the previous chapter. According to the age model, the dune covers a time span of approximately 100 years. Migration rates between each time interval were calculated from the spatial distance between the toe of the dune in the different aerial images.

## 3.3.3. Evaluation of wind and precipitation data

Weather data was obtained from a meteorological station located in List (Sylt). This station was originally located in the harbour area (55°00'41", 08°24'57"). Then, in 1964, it was relocated to an inland position called Mövengrund (55°00'48", 08°24'47", Fig. 3.1C).

The data investigated were wind speed and direction, as well as precipitation. Both time series cover the time period between 1937 and 2009, with a data gap between 1945 and 1947. The time series of the precipitation was based on daily measurements and for the wind strength and direction, three measurements per day were available. For better comparison with the precipitation data, daily means were calculated. The wind strength is given in the Beaufort scale. The inconvenience of this dataset is that it suffers from the inhomogeneity problem. This term refers to the influence of changes in the surroundings due to relocation of the station, changes in the instruments and/or in the observation practices which can lead to the contamination of the data by showing unrealistic trends (Alexandersson et al., 1998; Krueger and von Storch, 2011; von Storch, 2012). The inhomogeneities present in this dataset are likely due to the measuring procedure, since the Beaufort scale is based on observational data. Despite the presence of inhomogeneities, this dataset was used, as it covers a long period of time, which is required for a direct comparison with the architecture of the dune.

#### 3.4. Results

#### 3.4.1.GPR data

Seven radar facies (Rf) are identified (Fig. 3.2). These radar facies are subdivided into three different categories according to their configuration: inclined, horizontal, and irregular reflections. Additionally, four radar surfaces (Rs) are also determined (Fig. 3.2), which define discontinuities in the sedimentary architecture. The GPR profiles are interpreted with a vertical exaggeration of 2-times, but the dipping angles provided are corrected for this vertical exaggeration.

Out of the 18 GPR profiles collected, one was chosen to describe in higher detail the main architectural features. Figure 3.3 shows a terrain model of the investigated dune with the position of the GPR lines.

Radar Facies							
A. Inclined reflections							
	A1: low to high amplitude, continu- ous, parallel, slightly concave shaped, dip 10 to 20°	A3: low to high amplitude, continu- ous to discontinuous, parallel, convex shaped, dip 8 to10°					
A2	A2: medium to high amplitude, continu- ous, parallel, planar, dip 10 to 18°	44: low to high amplitude, continous to discontinuous, parallel, convex shaped, dip 10 to 22°					
B. Horizontal reflections							
BI	B1: medium to high amplitude, continu- ous, parallel to divergent, planar	B2: high amplitude, continuous; cutting other radar facies					
C. Irregular reflections							
C1: low to high amplitude, discontinu- ous, oblique chaotic							
Radar Surfaces	Figure 3.2: Radar facies and radar						
<b>S</b>	S1 Erosional truncation: high amplitude reflection, continuous, slightly concave shaped; separating two sedimentary bodies characterized by different dipping angles	surfaces identified in the GPR data. The radar facies are divided into three categories according to their geometrical shape into inclined, horizontal, and irregular reflections.					
S2	S2 Downlap: high amplitude reflection, continuous; overlying reflections terminating against this surface with a higher dipping angle than the underlying reflections						
53	S3 Toplap: medium to high amplitude reflection, continuous; underlying reflections bounded by low angle reflections						
	S4 Deflation surface: high amplitude reflection, continuous; overlying reflections: parallel, continuous, inclined reflections;						

#### Profile GWD-08

Profile GWD-08 is a longitudinal profile 380 m long (Fig. 3.4) and it is orientated parallel to the prevailing wind direction (WNW-ESE). Here, the dune reaches a maximum height of 22 m msl. The dipping angle of the reflections varies between 8° (Rf-A4) and 22° (Rf-A6). The amplitude of the reflections ranges from low to high, although high amplitude reflections predominate throughout the dune's body. Along the dune, the reflections are of three different shapes: concave, tabular, and convex. According to these geometrical patterns, three sedimentary units are distinguished.

The first unit is present from the beginning of the profile to approximately meter 50. This unit is characterised by concave shaped reflections of low to high amplitude and dipping angles
between 10 and 20° down to 2 m msl (Rf-A1). Here, a high-amplitude horizontal reflection occurs (Rs-S4) truncating the Rf-A1 reflections, which show a downlap configuration. At meter 40 of the profile, Rs-S4 reaches down to 0.5 m msl and continues at this height throughout the rest of the profile. Besides Rs-S4, Rs-S1 and Rs-S2 are also present. The radar surface S2 is defined as overlying reflections downlapping on it, whereas S1 is characterised by truncating the underlying reflections. In this unit, Rs-S1 appears truncating Rs-S2.

The second unit occurs between meter 50 and meter 140 of the profile. It is characterised by tabular reflections (Rf-A2) with medium to low amplitude and dipping angles varying between 10 and 18°. Reflections can be followed up to an altitude of 2 m msl. At this position, a high amplitude, horizontal reflection (Rf-B2) occurs. Between 0.5 and 2 m msl, some reflections can be identified. However this interval is characterised by the presence of hyperbolas hindering a proper interpretation.



Figure 3.3: Overview of the investigated dune with the position of the GPR lines.



Figure 3.4: A: WNW-ESE oriented GPR line GWD-08. For exact location see Figure 3.3. On top, the identified radar facies and radar surfaces are shown. B: Line drawing and interpretation of the GPR line provided in A. The dashed lines represent the internal bedding, whereas the colored lines indicate the surfaces found in the dune. The black lines are the timelines obtained from the aerial images.

Non-aeolian sediments (mostly marine)



**Figure 3.5:** Aerial images showing dune migration over time. The GPR lines are shown as reference of the present position of the dune. Additionally, neighboring dunes were also identified.

At 0.5 m msl Rs-S4 occurs. Irregular reflections (Rf-C1) appear in this unit, around meter 120 and 140 of the profile, extending vertically from the ground to the surface of the dune. Radar surfaces S1 and S2 are also present.

The third unit extends from meter 140 until the end of the profile. This unit is characterised by convex-shaped reflections. The lower part of this unit, up to a height of 10 m msl, presents high dipping angles (Rf-A4), whereas from 10 to 20 m msl high, the dipping of the reflections decreases (Rf-A3) turning to horizontal at the crest of the dune (Rf-B1). Reflections in this unit present a downlap configuration on Rf-B2, which occurs at a height of 2 m msl. As in the second unit, Rs-S4 is identified at 0.5 m msl. Additionally, Rs-S2 and Rs-S3 are found in this unit. Moreover, Rs-S3 is usually present in pairs, depicting a wedge shape.

#### 3.4.2. Aerial images

Aerial images covering the investigated area are available for 1936, 1944, 1958, 1965, 1988, 1998, 2003, and 2009. Figure 3.5 presents four aerial images together with the position of the GPR lines, to show the landward migration of the dune over time. The GPR lines act as a reference of the current position of the dune.



It is also evident how the vegetation has increased colonizing neighbouring small dunes. The neighbouring dunes are identified as D2.1, D2.2 and D2.3. Dunes D2.1 and D2.2 have almost disappeared from 1936 to 2003, being at the present completely covered by vegetation. In case of D2.3, its size has been drastically reduced. The area of the investigated dune has also decreased; this is mainly due to the increase of vegetation in the southernmost part of the dune, causing the separation of the main dune body. Figure 3.6 depicts changes on the size of the dune together with the vegetation cover. The aerial image of 1936 shows that the dune had an area of 651000 m<sup>2</sup>, of which 9000 m<sup>2</sup> were vegetated. In 2009, the area of the dune was 349000 m<sup>2</sup> and the vegetation coverage increased by ten times. This increase in vegetation occurs especially on the northern and southern sides of the dune as well as on the crest.

The migrating velocity of the dune over time was calculated by considering the time span of the available aerial images and the position of the toe of the dune in each aerial image, using the position of the GPR lines as reference. Figure 3.7 represents the migrating velocity of the dune for the time intervals covered by the aerial images. The mean migrating velocity of the dune between 1936 and 2009 was 4.1 m/yr. In general, during the studied period an increase of the mean migrating velocity was observed.



**Figure 3.7:** Graph representing the annual number of westerly winds > 3 Bft (red line) and the annual precipitation (blue line) between 1937 and 2009. Additionally, the dune migration rates are represented.

#### 3.4.3. Time series of wind and precipitation

A time series of wind and precipitation covers the time span between 1937 and 2009, with a gap between 1945 and 1947. Wind data show that westerly-southwesterly winds prevailed (Fig. 3.8). Despite the prevalence of westerly winds, some cross-winds periods from the SE were also identified. The wind strength varied between minimums of zero Beaufort (calm periods) to a maximum of almost 11 Beaufort. Wind strengths between 4 and 6 Beaufort occurred more often during the investigated period.



**Figure 3.8:** Wind rose showing the wind strength and wind direction between 1937 and 2009.

Since the dune migrates towards the east, erosional unconformities can only be formed by strong winds coming from easterly direction. Therefore, the number of easterly storms per year between 1937 and 2009 were counted (Fig. 3.9). A storm was defined as an event with wind strength greater than 7 Beaufort for this thesis. The results show that during the late 1930's and beginning of the 1940's the number of storms was much higher than in the remainder of the century. According to this, two subperiods were identified. An average of ten storms per year occurred between 1937 and 1944, with 1937 and 1941 being the years with the highest number of days with easterly storms. On the other hand, on average, only one easterly storm per year occurred between 1948 and 2009, with 1958 being the stormiest year with a total of six easterly storms. In addition, Table 3.1 presents the intensity and the exact dates of easterly storms that lasted more than two consecutive days. These strong easterly storms occurred more often during winter and spring seasons. Additionally, the number of days per year with winds higher than 3 Beaufort was also plotted (Fig. 3.7). The overall trend shows a slight increase over time. The time series of the precipitation rate shows a slightly increase on the total amount of precipitation per year over the last 72 years (Fig. 3.7). The years with the highest precipitation were 1974, with more than 1000 mm/yr, and 1966 and 1988, both with more than 900 mm/yr of precipitation collected. On the other hand, the driest years were 1959 and 1996, with less than 500 mm/yr collected. The time series were subdivided into two subperiods; the first, from 1937 to 1964, with a mean annual precipitation below 700 mm, and the second, from 1965 to 2009, with an annual mean above 700 mm.



Figure 3.9: Annual number of easterly storms (winds > 7 Bft) between 1937 and 2009

#### 3.5. Discussion

#### 3.5.1. Geomorphological change

Visual analysis of the aerial images for the time interval of 1936-2009 reveals that the investigated dune changed from a transverse to a parabolic dune (Fig. 3.10). In the aerial image of 1936, the toe of the dune shows a linear NNE-SSW orientation and it is characterised by the absence of vegetation. This is also depicted in the aerial image of 1944. In the aerial image of 1958 the toe of the dune still presents a linear NNE-SSW orientation. Further observation illustrates an increase of vegetation in the surroundings of the dune as well as at the crest of the dune, creating the so-called kupsten. The kupsten are vegetated hillocks present in the crest of the dunes, which are temporally stabilized due to vegetation cover, although they suffer from erosion because of the toe of the dune. In the following aerial images, it can be appreciated how the original linear shape of the dune. The bending is also evident on the increased spacing between timelines in the central part of the dune, in comparison with the outer part. The increase of vegetation produces the fixation of the outer part.

	Wind	Wind Strength	<b>D</b> /	Wind	Wind Strength		
Date	direction	[Bft]	Date	direction	[Bft]		
1937			1942				
18. Jan	SE	8.7	04. Mar	ENE	7		
19. Jan	ESE	10	05. Mar	ENE	8.3		
24. Jan	ESE	9	06. Mar	ENE	7.3		
25. Jan	ESE	9	07. Mar	ESE	8.3		
26. Jan	E	8.7	1943	-	-		
27. Jan	E	7	11. Jan	SE	7.7		
28. Jan	E	8.7	12. Jan	SE	7		
29. Jan	ENE	7.3	19. Mar	ESE	7.7		
30. Jan	E	7	20. Mar	ESE	7		
31. Jan	E	8.3	1958	-	-		
1938			27. Mar	E	7		
15. Dec	SE	7.3	28. Mar	ENE	7.7		
16. Dec	SE	7.3	29. Mar	ENE	7.7		
1939			30. Mar	ENE	7.7		
03. Nov	SE	7.3	1959				
04. Nov	SE	8	15. Dec	E	8.7		
09. Dec	SE	7.3	16. Dec	E	8		
10. Dec	ESE	8	1960				
1940			07. Mar	E	7.3		
30. Jan	ESE	7	08. Mar	E	7.7		
31. Jan	ESE	8	09. Mar	E	7.7		
01. Feb	E	7.7	1964				
28. Mar	E	7.3	13. Mar	E	7.7		
29. Mar	ESE	7.3	14. Mar	E	8.7		
30. Mar	E	7.3	15. Mar	E	7.7		
01. May	E	7.3	1969		•		
02. May	E	7	13. Mar	E	7.3		
1941			14. Mar	E	8		
28. Jan	E	7	15. Mar	E	8		
30. Jan	ESE	7.3	16. Mar	E	8		
31. Jan	ESE	7.3	17. Mar	E	7.3		
01. Feb	ESE	7	1979		•		
02. Apr	ESE	8	14. Feb	E	7.3		
03. Apr	ESE	8.3	15. Feb	E	7.3		
10. Oct	E	7	Table 3.1 Dat	e wind (	direction and		
11. Oct	NE	7.7	wind strength of the easterly storms				
11. Nov	ESE	9	while leaded many them two				
12. Nov	ESE	9.7	which lasted more than two days				
13. Nov	E	10.7	between 1937 and 2009.				

Consequently, the timelines in this area appear superimposed and the typical U-shaped form of a parabolic dune is developed. Based on the observation of the aerial images, the change in the morphology of the dune should have started before 1958 with the increase of the vegetation cover, although this was not evident until 1965. A more precise date is not possible to obtain due to the absence of aerial images during at the time.

ESE

ESE

8

7

14. Nov

15. Nov



**Figure 3.10:** Aerial image from 2009. The colored lines show the position of the toe of the dune in the past. It is observed how the shape of the toe changed from straight to curved after 1965 indicating the change from a transverse to a parabolic dune.

The change from a transverse to a parabolic dune is attributed to two factors: the reduction of sediment supply and the increase of vegetation. After the formation of this dune chain at the coast, due to its inland migration, it is assumed that the sediment supply was reduced until it was finally cut-off. This assumption is based on the fact that the youngest dune chain situated currently at the coast is high enough to hinder the sediment transport from the beach area to the

investigated dune. Additionally, sediments samples analysed at a later stage of this research have revealed the absence of fine sediment, which would evidence an input of new sediment. Therefore, it is inferred that due to the absence of sediment supply as the dune migrates, the sediment forming the dune is reworked and thus, the dune size decreases. Considering the vegetation cover, it is observed that it has increased almost 10 times from 1936 to 2009. The increase of vegetation on the sides of the dune causes the anchoring of these outer parts whereas the central part of the dune continuous migrating, favouring the development of the typical U-form of the parabolic dunes. Moreover, vegetation can also trap sediment, increasing the reduction of sediment in the studied area. In Figure 3.6 it is illustrated how the dune area in 2009 is approximately 349000 m<sup>2</sup> and the vegetation cover is about 31000 m<sup>2</sup>. However, in order to be able to compare all the aerial images, in 2009 an area of 447000 m<sup>2</sup> and a vegetation cover of 86000 m<sup>2</sup> should be considered. This increase of the areas arises from the addition of the southernmost part of the dune that, at the present time, it is almost completely vegetated and thus, it does not belong anymore to the current active dune.

Hugenholtz et al. (2008) investigating the stratigraphy of active parabolic dunes in Canada, also attributed to the increase in vegetation and to the decrease of sediment supply the responsability of changing dune form in an inland setting. They illustrated how under high sand supply, the colonization of the dune's head by vegetation is diminished, leading to rapid sedimentation and dune migration (Fig. 3.11). Under these assumptions the dune profile will show a relatively short crest-brink separation and a steep lee slope. In the stratigraphy, high-angle cross-strata will predominate due to the deposition by grain flow on the lee slope. When the sediment supply decreases and the vegetation cover increases, the dune form will respond by developing a short stoss slope and by increasing the crest-brink separation. Sediment deposition on the lee slope will occur mainly by grain fall and ripple migration and the stratigraphy of the dune will be dominated by a low-angle cross-strata. A geomorphological change of dune form from transverse to parabolic reported by Tsoar and Blumberg (2002). who investigated coastal dunes along the Israel's coast, attributed the change in geometry to the increase in vegetation. In their investigation, they observed a change in the windward slope from convex to concave due to this geomorphological change. Part of the eroded sand from the windward side will be retained by the established vegetation at the crest and it will not reach the depositional area on the lee side. Consequently, the dune will lose its dynamic equilibrium.

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**Figure 3.11:** Diagram showing the effects of sand supply and vegetation cover on the dune morphology and stratigraphy (after Hugenholtz et al., 2008).

The sand is accumulated on the crest forming kupsten, and due to the erosion on the windward side, the change on the windward slope occurs. This observation cannot be recognized in any of the data presented in this research. However, Priesmeier (1970) presented two cross sections of the investigated dune corresponding to the years 1925 and 1968, in which this change on the windward slope can be appreciated. This observation confirms the reported dates based on the aerial images for the geomorphological change.

Variations of the vegetation cover are usually related to humidity. Therefore, the increase of the vegetation cover was compared to the variations in precipitation rate. In the precipitation time series, the annual precipitation increased after 1964. This increase may have triggered the increase in vegetation cover, which afterwards caused the geomorphological change. However, the anthropogenic factor should not be excluded. Due to coastal protection plans, vegetation was introduced in northern Sylt. This action was done to force the stabilization of other migrating dunes located in the surrounding area of the investigated dune.

#### 3.5.2. Sedimentary architecture

#### 3.5.2.1. Architectural elements

The sedimentary structures present in dunes can be classified into two groups: primary and secondary structures. Primary structures are those reflecting the processes responsible for transport and deposition of the sand, whereas the secondary structures show post-depositional processes (Pye and Tsoar, 2009). In accordance with that, the foresets of the dune represent primary structures, whereas the different unconformities constitute secondary structures.

The GPR line GWD-08 images the main architectural elements of the dune. Due to its orientation, parallel to the wind direction, it is observed that the dipping of the foresets show a continuous progradation of the dune towards the east. The dipping angle of the foresets varies in the vertical axis from moderate (up to 22°) in Rf-A4 to low (<10°) in Rf-A3 turning almost horizontal towards the crest of the dune (Rf-B1). This decrease of the dipping angle from the base of the dune to the top is associated to the progradation of the dune. As the dune migrates, the sand tends to accumulate towards the front of the dune, in the basal part, rather than in the upper part. Such variation of the dipping angle was also observed by McKee (1966) in the parabolic dunes of White Sands in New Mexico.

Secondary structures can result from slumping, bioturbation and/or erosional processes (Mckee et al., 1971; McKee and Bigarella, 1972; Pye and Tsoar, 2009). In this study four radar surfaces are identified (Fig. 3.2). Following the approach of seismic interpretation (Mitchum et al., 1977), the secondary structures are classified according to the termination of the reflections in: erosional truncation, downlap, and toplap.

Based on the age model, no erosional truncations are present after the year 1944. Considering the continuous progradation of the dune towards the east, due to the prevailing of westerly winds, this kind of surface can only be formed due to strong easterly winds being able to erode the lee side of the dune. A correlation with the wind data showed that strong easterly storms (winds stronger than 7 Bft) occurred predominantly during the late 1930's and beginning of the 1940's (Fig. 3.9). Afterwards, the annual number of these events decreased significantly, especially after 1970. Considering the duration of the easterly storms (see Table 3.1) it is recognized that in order to produce significant erosional unconformities, very long lasting events like the ones observed in 1937 and 1941 are necessary. Strong easterly winds acting during only a few days will not cause a significant erosional unconformity. This would explain why after 1944, no erosional truncations occurred. Downlapping surfaces are the most common secondary structures present throughout the whole dune. This kind of surface is also known as a growth surface (Harari, 1996). The reflections above this surface show a downlap geometry, reflecting the dune's accretion. Toplap surfaces occur only after 1965. They appear depicting sediment packages characterised by wide cross-strata in the lower part of the dune turning thinner towards the crest of the dune. In the most extreme case, this thinning ends in the central part of the sedimentary body depicting a wedge shape. Studies in the parabolic dunes from White Sands (McKee, 1966) and from different dune fields in Brazil (Bigarella et al., 1969; Bigarella, 1975) also found a thinning of the cross-strata from the basal part towards the top, where they

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become thinner and flatter. The toplap surfaces could be explained by sediment erosion on the lee side; however, this is very unlikely in the dune of Sylt due to the absence of erosional unconformities. Otherwise, a feasible explanation for that would be related to the development of the convex nose due to cross winds causing a higher accumulation of sediment in the lower part of the dune. Cross winds from the south-easterly direction would accumulate sand in the nose of the dune, causing a thickening of the basal part of the sedimentary body. An analysis of annual wind roses, corresponding to the years in which these structures might have formed, shows higher variations in the wind direction. In addition to the prevailing westerly winds, south-easterly winds also occurred frequently. These south-easterly winds of limited duration were not strong enough to generate erosion and hence, sand deposition occurred. Thus, this kind of structures could also be an indicator for years with higher wind direction variability.

#### 3.5.2.2. Dune geometry

Amongst the different kinds of structures identified in the internal architecture of the dune, two geometrical changes are also observed. The first one is the change from concave to tabular foreset geometry between the first and second unit described in the GPR-line GWD-08 (Fig. 3.4). However, this geometrical change cannot be traced throughout the whole dune due to the presence of a palaeodune. Therefore, no further analysis is done. The second one is the change from tabular to convex foreset geometry, separating the second and the third unit defined in GWD-08. In this case, this change is identified in all GPR-lines oriented perpendicular to the dune crest, as sketched in Figure 3.12. In addition, it can also be identified in two of the longitudinal GPR-lines (Fig. 3.13). Figure 3.13A, the timelines based on the aerial images (colored shows the GPR line GWD-D and corresponds with the tabular geometry.



Figure 3.12: Sketch of the present dune shape with lines). The blue dots represent the position of the geometrical change in each GPR line.

Whereas Figure 3.13B shows GWD-E which represents the convex geometry. Therefore the internal bedding appears bent on the sides. The geometrical change occurs shortly after 1965, except in GWD-01 and GWD-02, the northernmost GPR lines. 1965 is also the year in which the geomorphological change is more evidenced on the aerial images. This led to the conclusion that the change of the internal geometry reflects the change from a transverse to a parabolic dune.



**Figure 3.13:** Roughly interpretation of two longitudinal lines to illustrate the geometrical change. GPR profiles are shown with a vertical exageration of 5-times. **A:** GWD-D profile represents the tabular geometry. **B:** GWD-E profile represents the convex geometry.

However, this change did not occur in the whole dune at the same time. The sides of the dune are more sensitive to the geomorphological change and thus, the geometrical change in GWD-01 and GWD-02 is observed before 1965. McKee (1966) observed in his study about the dunes of White Sands in New Mexico that tabular cross-stratification dominated on the transverse dunes whereas convex foresets were identified in the front of parabolic dunes. This feature was not observed in any other kind of dunes, i.e., transverse or barchans, also present in that area. This convex front is explained as a result of the dune shape. The nose of the parabolic dune is more exposed to the occasional cross winds, thus an oversteepening of the foresets will occur, causing the convex shape. Other studies carried out by Halsey et al. (1990) and Hugenholtz et al. (2007, 2008) also found that the convex front is a characteristic of parabolic dunes.

#### 3.5.3. Dune morphodynamics

The analysis of the aerial images shows that in the last 73 years the dune has migrated eastward without suffering any directional shift. Besides, the dune size has decreased by approximately 45% of the size observed on the aerial image of the year 1936. Considering the current coastline, the dune has migrated approximately 900 m inland, with a mean migrating velocity of 4.1 m/yr. The migrating velocities calculated within the different aerial images show that the migration velocity has increased from 3.4 m/yr for the period of 1936-1988 to 5.1 m/yr for the period of 1988-2009. This fact suggests that the increase on migration velocity is directly related to the decrease of the dune size. This correlation was also observed by Jimenez et al. (1999), who investigated migrating dunes in the coast of Brazil and found that migration rates were strongly dependent on the dune size: the smaller the dune is, the higher the migration rate will be.

Despite the general increase of the migration rate over the entire studied period, it is observed that this increase is not linear. Dune migration is a complex process affected by other factors such as wind strength and direction, sediment supply, vegetation or precipitation (McKee, 1979; Lancaster, 1992; Girardi and Davis, 2010). Therefore, these factors should also be taken into consideration when discussing variations of the dune morphodynamics. The decrease of the sediment supply and the increase of the vegetation cover have already been discussed as triggers of the dune size reduction and would then be related to the observed increasing trend of the migration velocity. Figure 3.7 represents the number of days per year with westerly winds higher than 3 Beaufort, the annual precipitation, and the migration rates calculated based on the aerial images. A wind speed of 3 Beaufort is chosen, as this is the threshold value to transport

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a mean grain size of 1.3 phi, like the minimum grain size present in the dune (Hunter et al., 1983; Arens, 1997; Lancaster, 1997; Delgado-Fernandez and Davidson-Arnott, 2009, 2011). Three different periods can be identified according to a low, a medium, and a high migration velocity. The first period goes from 1936 to 1958 and it is characterised by a medium migration velocity, with an average migration velocity of 4.2 m/yr. During this period, the number of days with winds higher than 3 Beaufort is low, less than 200 days/yr, and the annual precipitation is also low, with a mean of 650 mm/yr. The second period, between 1958 and 1988, presents the lowest migration rates, with a mean migration velocity of 2.7 m/yr. Despite an increase of the annual ocurrance of days with winds higher than 3 Beaufort, approximately 200 days/ year, the annual precipitation presents its highest values, with a mean of more than 700 mm/ yr. The last period, between 1988 and 2009, presents the maximum migration rates, with a mean of 5.1 m/yr. During this period, the number of days with winds higher than 3 Beaufort presents the highest values, with more than 200 days/yr, and the annual precipitation suffers a decrease, with a mean value of approximately 700 mm/yr. These results show that there is not a direct correlation between the migration rates and the variations on the occurrence of winds higher than 3 Beaufort and the annual precipitation. Despite this, it would be expected that an increase of the windy days would cause an increase of the migration rates. But in this case, the precipitation is the factor which modulates the variations of the migration rates: assuming a similar amount of windy days capable of transporting sediment, the migration rate will be determined by the annual precipitation. If the annual precipitation is low, high migration velocities would occur, whereas if the annual precipitation is high, the migration velocity will be low. Between 1937 and 2009, an average of 58% of the year, the wind was capable of producing sediment transport. Therefore, sediment transport is not limited by the wind duration and velocity, but by the precipitation. Furthermore, Forman et al. (2008) investigating dunes in Massachusetts (USA), found an apparent relation between accelerated dune migration and dry conditions. Under dry conditions, dunes migrate faster.

#### 3.6. Conclusions

This study presents the external and internal evolution of a migrating dune located in northern Sylt. The investigation based on aerial images, shows how the dune changed from a transverse to a parabolic dune. During this transformation, the dune size was reduced by approximately 45%. This geomorphological change occurred between 1958 and 1965 and it is attributed to the reduction of the sediment supply and the increase of vegetation cover. In addition, an increase of the annual precipitation after 1964 was a possible trigger for the increase of the vegetation cover. However, due to coastal protection plans, vegetation was introduced in northern Sylt.

Thus, an anthropogenic explanation as possible cause of the increase of vegetation cover cannot be excluded.

The internal architecture of the dune shows a change from tabular to convex foresets geometry. This change occurred after 1965, except on the northernmost side of the dune, which indicates that the sides of the dunes are more sensitive and will react faster to changes. This geometrical change reflects the geomorphological transformation from a transverse to a parabolic dune. Transverse dunes are characterised by tabular bedding, while parabolic dunes are characterised by convex noses, causing the convex bedding. Additionally, architectural elements, such as erosional unconformities or toplap geometries, are also identified in the dune representing specific wind characteristics. Due to the constant eastward migration of the dune, erosional unconformities can only be generated by long-lasting easterly storms. This situation occurred during late 1930's and early 1940's, the same period in which erosional unconformities were formed in the dune. The toplap geometries are characterised by defining sediment packages with a higher sediment accumulation in the basal part of the dune than in the upper part, defining a wedge shape. It is interpreted that these packages were caused by cross winds capable of accumulating sediment in the basal part of the dune, but due to its low intensity or short duration, they were unable of producing erosion. Therefore, the toplap geometries could be an indicator of periods with higher wind direction variability.

Dune migration is a complex process influenced by the interaction of sediment supply, vegetation cover, wind intensity, and precipitation. In general, it is observed that the migration velocity of the dune increases due to the decrease of the dune size. However, during the investigated period, three different migration rates are distinguished: low (2.7 m/yr), medium (4.2 m/yr), and fast (5.1 m/yr). These differences seem to be related to the interaction between the number of days per year with westerly winds higher than 3 Beaufort and the annual precipitation, with the latter being more influential. Those years with a medium occurrence (number of days per year) of westerly winds higher than 3 Beaufort (~ 200 days/yr) and a high annual precipitation (>700 mm/yr), have low migration rates. However, when both, occurrence of westerly winds and annual precipitation, are low (< 200 days/yr and ~650mm/yr), medium migration rates occur. The highest migration rates are found during periods of high occurrence of westerly winds (>200 days/yr) and medium annual precipitation (~700 mm/yr).

### **Chapter 4**

# Reconstruction of wind-field variations recorded in sediments of a migrating dune

#### Abstract

The aim of this study is to reveal a new archive of temporal wind-field variations recorded in sediments of migrating dunes. To reach the aim, proxies for wind-speed variations obtained from sedimentological data are compared to instrumental observations. The study area is situated in the northern part of Sylt island (southern North Sea). This study focusses on a migrating dune, which is approximately 900 m long and 35 m high. The annual rate of dune movement is around 4.1 m per year. For sedimentological analyses, a 238 m long trench orientated in the direction of the dune movement (W-E) was sampled every 5 cm at a mean depth of approximately 50 cm on the windward side of the dune. The parameters used for the statistics are mean grain size and sorting. Additionally, an age model was created based on a series of aerial images. Instrumental wind data is available from a meteorological station situated nearby the study area, ranging back to the year 1950.

The comparison between the sedimentological and the instrumental wind records shows that comparable trends are recorded in the dune. An overall trend from fine to coarse and from well to poorly sorted sediment is observed towards the crest. Well sorted samples are related to weak wind speed, whereas poorly sorted samples are related to strong wind speeds. A function describing the relation between both datasets is defined. Based on this sedimentological record, wind-speed variations back to 1907 are reconstructed with a decadal resolution. Besides, a wavelet power spectrum is applied to study the presence of cyclicities inside the different datasets. Results show that bianual and annual cycles are present in both datasets, defining a change in sorting from well to poorly to well sorted, and a variation in wind speed from low to high to low. In addition, a correlation between a 3.6 and a 6 yr cycle, present in the sedimentological record, and a 5 and a 8.5 yr cycle, present in the wind-speed record, is interpreted. Considering the periods of these cyclicities, a potential reason for their occurrence could be linked to variations of the North Atlantic Oscillation (NAO).

#### 4.1. Introduction

The development and migration of coastal dunes is strongly affected by changes in wind strength and direction, sediment supply, and vegetation (Orford et al., 2000; Labuz, 2004; Anthony et al., 2010; Girardi and Davis, 2010). Consequently, they are quite sensitive to climatic changes (Pye, 1983; Havholm et al., 2004; Baas, 2007) and they can constitute important palaeoclimatic records (Clemmensen et al., 2007; Sommerville et al., 2007; Porat and Botha, 2008; Pye and Blott, 2008; Levin et al., 2009; Tsoar et al., 2009; Tamura et al., 2011). These studies are mostly focused on large-scale fluctuations to identify periods of dune activation and stabilization, specially related to the Little Ice Age (LIA) (Clemmensen et al., 1996, 2001b, 2001c; Wilson et al., 2001; Ballarini et al., 2003; Aagaard et al., 2007; Szkornik et al., 2008; Forman et al., 2009; Costas et al., 2012). However, studies investigating the recent past (<100 yr) are not common. They usually evaluate the sand drift potential following the Fryberger's method (Fryberger and Dean, 1979) to estimate the sand transport and to evaluate the impact of potential climate changes (Anthonsen et al., 1996; Panario and Piñeiro, 1997; Yizhaq et al., 2009).

This study aims to access a new archive of temporal wind-field variations recorded in a migrating dune located in the island of Sylt (southern North Sea). This record will be used in a later stage as a proxy for reconstructing wind-field variations in absence of instrumental data. To reach the aim of this study, an integrated approach combining geophysical, sedimentological, and statistical methods is applied. Ground-penetrating radar (GPR) is used to reveal the sedimentary architecture of the dune providing information about direction of dune movement in the past. This method was succesfully applied in previous studies to detect sedimentary structures on a high-resolution scale (Bristow et al., 1996; Harari, 1996; Bailey and Bristow, 2000, 2000; Botha et al., 2003; Lindhorst et al., 2008). Sediment samples collected each 5 cm at the subsurface of the windward side of the dune constitute the sedimentological record. Additionally, an age model based on aerial images is required to assign ages to the sedimentological station situated nearby the investigated dune. After this correlation, a model is developed to describe the relationship between both datasets and it is used to reconstruct the wind-field variations in time periods without instrumental data.

#### 4.2. Study area

Sylt is an island situated in the southern North Sea and it is located 15 km off the German coastline, near the border with Denmark (Fig. 4.1). The island is formed by a moraine core (Gripp and Simon, 1940). Two large sandy spit systems occur attached to the northern and to the southern edges of the core forming an elongated island 38 km long. The northern spit is characterised by fixed and active dunes that can reach up to 35 m in height. Due to the prevailing westerly winds the dunes are oriented ~NNE-SSW. The winds between 225° and 315° are dominant and the average wind speed is around 7 m/s. This dune system was first investigated by Priesmeier (1970) following a geomorphological approach. According to this approach a new generation of sand dunes accumulates every 300 yr along the western coast and then start migrating towards the east. Therefore, he proposed that the dune growth and the migration are cyclic. The main sediment supply comes from the longshore currents transporting sediment eroded from the moraine core (Gripp, 1944; Dietz and Heck, 1952). When each generation of dunes starts migrating inland, the sediment supply is interrupted. Thus, the sediment which forms the dunes will suffer a continuous reworking leading to a limited sediment pool in the present migrating dunes.

The studied active dune is situated in the northern spit and it is oriented in the NNE-SSW direction. It is situated 900 m away from the west coast of the spit and it is approximately 900 long and between 400 and 500 m wide.

#### 4.3. Methodology

#### 4.3.1. Ground-penetrating radar (GPR)

A ground-penetrating radar (GPR) was used to image the internal architecture of the studied dune. The GPR is a non-invasive method used for surveying the shallow subsurface with centimetre to decimetre resolution , which has proved to be a valuable tool for studying internal structures in dunes (Bristow et al., 2005; Lindhorst et al., 2008; Girardi and Davis, 2010). A Geophysical Survey Systems Inc. radar system SIR-3000 was used with an antenna frequency of 200 MHz. Radar data were collected in a continuous mode with a survey wheel as distance trigger. Trace increment during data acquisition was set to 5 cm and 2048 samples were collected for each shot. Manufacturer settings for frequency filtering and no stacking were applied during data collection.



**Figure 4.1: A:** Sketch of the north-western Europe region with location of Sylt. **B:** Digital Terrain model of northern Sylt obtained with an airbone LIDAR from the ALR Husum in 2002. The terrain model has a cell size of 1 m and a vertical accuracy of 0.2 m. It is also shown the position of the studied dune and the location of the meteorological station. **C:** Aerial image from 2009 of the investigated dune. The dashed lines display the GPR profiles collected during the field campaign carried out for the whole investigation, the thick black line refers to profile GWD-08, which is the one presented in this chapter, and the thick red line shows the transect where the sediment samples were collected.

Processing of the raw data was done using the software ReflexW (Sandmeier, v. 6.0, 2008) to enhance the signal-to-noise ratio. The processing comprised correction of time-zero offset, frequency bandpass filtering, background removal, gain adjustment, and migration. Based on fitting diffraction hyperbolas an average subsurface velocity of 0.13 m/ns was estimated, which is a common value for dry sands (Jol and Bristow, 2003). Correction for topography was also

applied to restore different terrain altitudes and to be able to interpret correctly the sediment geometries. The data necessary for the topographic correction was obtained with a differential global-positioning system (Ashtech ProMark II). In total, 18 profiles were collected with the GPR.

#### 4.3.2. Dating

An age model is required to understand the development of the studied dune. Aerial imagery can provide important information regarding dune growth and migration in aeolian dunes, complementing the high-resolution information obtained from the GPR data (Bristow et al., 2005; Hugenholtz and Wolfe, 2005; Hugenholtz et al., 2008; Girardi and Davis, 2010). To build up this age model, eight aerial images were processed and georeferenced using the ArcGIS software (ESRI, 2008). The aerial images were taken in 1936, 1944, 1958, 1965, 1988, 1998, and 2003. The toe of the dune along the lee side was digitized and then those points were projected on the radargrams following the foresets of the dune to obtain the age model on the dune surface. The accuracy of the location of each isochrone is  $\pm 1-2$  m.

#### 4.3.3. Sedimentological methods

In order to obtain a sedimentary record, sediment sampling was carried out along a 245 m long transect oriented parallel to the dune movement. Samples were collected equidistantly every 5 cm at a depth of approximately 50 cm below the surface. Collecting samples at such a depth allows sampling an undisturbed surface, which will provide the correct sedimentological information about the sediment deposition. To analyse the samples a Sympatec Helos/KF-Magis laser diffraction particle-size analyser was used. Afterwards, the sedimentological parameters were evaluated using the program Gradistat (Blott and Pye, 2001). The results are based on the graphical logarithmic method by Folk and Ward (1957).

#### 4.3.4. Evaluation of wind data

Wind data were measured by a meteorological station situated in List, which belongs to the Deutschen Wetterdienst, and it is located nearby the study area (Fig. 4.1). This station was situated until 1964 in the harbour area. In order to demonstrate the reliability of the wind data and to distinguish between natural variability and anthropogenic effects due to e.g. changes in the station location, it is necessary to prove that the data is homogenous. A previous study based on this dataset (Lindenberg et al., 2012) demonstrates that, despite the change in the

location of the station, the meteorological data is homogeneous and thus, the use of this dataset is appropriate. This meteorological record covers the time period since 1950. It provides hourly information of wind speed and wind direction as well as daily values of precipitation. In order to process the dataset, daily and weekly means of the wind were calculated.

#### 4.3.5. Statistical methods

One of the prerequisites for dune migration is the occurrence of winds capable of transporting the available sediment. Before sand transport by the wind occurs, a threshold wind speed should be reached to initiate the sediment movement. According to Bagnold (1941), the threshold shear velocity for dry sand to set sediment to motion can be calculated by the following equation

$$u_{(t')} = A \cdot \sqrt{\frac{(\rho_s - \rho_a)}{\rho_a} \cdot g \cdot D} \qquad \qquad \text{Eq. (1)}$$

where  $\rho_s$  is the density of sand,  $\rho_a$  is the density of the air, D is diameter of the grain, g is the gravity constant, and A is a constant (A=0.12). Thus, as the mean grain size increases, the threshold velocity also increases. Changes in moisture content are especially important at low wind speeds, when moisture plays a relatively greater role in inhibiting entrainment (Jackson and Nordstrom, 1997). Therefore, the threshold shear velocity for wet sediments should be calculated, since it will increase if the precipitation exceeds the evaporation (Hsu & Weggel, 2002).

$$u_{(t'w)} = u_{(t')} + 18.75$$
 [cm/s] Eq. (2)

in which  $u_{(t)}$  is the critical shear velocity for dry sediments and 18.75 cm/s is a value obtained from the fraction of water present in the upper 5 mm of sand, assuming that this fraction is smaller than the 2.5% (Svasek and Terwindt, 1974; Hotta et al. 1985).

After calculating the threshold shear velocity, which will set a certain grain size to motion, it is possible to extrapolate it to any measured height using equation 3 to calculate the threshold mean velocity to find the wind velocity necessary to transport sand.

in which  $u_z$  is the average wind speed as a function of height above ground level,  $u_{(t)}$  is the critical shear velocity,  $\kappa$  is the Von Karman's universal turbulent layer constant ( $\kappa$ =0.40), z is the height at which  $u_z$  was measured (in this case 10 m, which is the height of the meteorological station), and  $z_0$  is the aerodynamic roughness length.

Cross-correlation analyses between the sedimentological and the meteorological records were done using the program AnalySeries (Paillard et al., 1996). In order to do this cross-correlation three sorts of files are required: a pointer file, a distorted file, and a reference file. The meteorological record acts as the reference file, since it is the dataset where the exact dates are known, whereas the sedimentological record is the distorted file. The pointer file is formed by the age model based on the aerial images. This file allows connecting the reference and the distorted file. It is formed by one column which indicates the exact date when the aerial image was taken, and another column which reflects the corresponding position of the aerial image on the dune surface. Afterwards, the cross-correlation can be improved by adding some extra pointers based on pattern fitting. This cross-correlation step also allows converting the sedimentological record from a thickness-based series to a time-bases series.

Wavelet analysis can be used to detect periodic-cyclic sequences in geological time series (Prokoph and Barthelmes, 1996). Thus, the procedure described by Torrence and Compo (1998) using MATLAB (MATLAB, v. 7.8.0, 2009) was applied to investigate the presence of cyclicities in the sedimentological as well as in the instrumental records. It has been observed that wavelet power spectra are biased, favouring large scales or low frequencies (Torrence and Compo, 1998b). Thus, the modification introduced by (Liu et al., 2007), consisting on normalizing the wavelet power spectrum dividing it by the corresponding scale, was applied.

#### 4.4. Results

#### 4.4.1. Dune architecture and chronology

Out of the 18 profiles collected with the GPR, only profile GWD-08 is investigated in this part of the study. Along part of this profile sediment samples were also collected. The architectural elements investigated in this section are erosional unconformities and toplap geometries. These geometrical features are chosen because they can denote an incomplete sedimentological record and thus, affect the correlation between the sedimentological and the wind-speed records due to the absence of a continuous sedimentation.







Figure 4.2 shows the GPR line investigated and its interpretation, together with the age model based on the aerial images. The GPR profile has a length of 380 m and reaches a maximum height of 22 m msl. It has a vertical resolution of 16.25 cm, which allows a precise interpretation of the internal geometries. However, the signal in the lower part of the profile, between 160-180 m of the profile, is attenuated due to the presence of an artefact which hinders the interpretation in this area.

Data show that erosional unconformities occur mainly in the older part of the dune, before 1944. Considering the toplap geometries, eleven are found along the profile, all occurring after 1965.

Based on the position of each isochrone, it is possible to estimate the migration velocity of the dune in each single profile and then, to calculate the mean migration velocity of the whole dune (Table 4.1). The result shows that the mean migration velocity of the whole dune, between 1936 and 2009, is 4.1 m/yr.

**Table 4.1:** Migration velocities of the investigated dune calculated based on the aerial images. It shows the relative migration velocity of profile GWD-08, where the sediment samples were collected, and the absolute migration velocity computed considering all the collected profiles.

	1936-1944	1944-1958	1958-1965	1965-1988	1988-1998	1998-2003	2003-2009
GWD-08	1.4	2.6	4.8	3.1	5.3	3.4	6.1
Whole Dune	4.4	3.9	2.7	2.7	6.7	3.2	5.4

#### 4.4.2. Sedimentological record

The sedimentological record is formed by 4900 samples collected at a depth of 50 cm along a 245 m long trench. A comparison with the GPR data shows that the last seven meters of the trench are located at the crest of the dune. This area is characterised by reworking of sediments. Therefore, the samples corresponding to this area were rejected to avoid a misinterpretation of the data. The remaining samples were analysed and, after losing some of them during the measurement procedure and rejecting some other due to unlikely statistical results, 4734 were used as sedimentological record. The statistical parameters investigated are the mean grain size and the sorting. In Figure 4.3 the mean grain size and sorting variations with a 5-point running mean are shown, together with the GPR interpretation and the age model based on the aerial images. This figure gives an overview of the relation of the sedimentological parameters

obtained from the collected samples regarding the dune architecture and the age model. The grain size varies between 1.80 and -0.34 phi, being the lower values the ones showing coarser grains. The mean grain size, d50, of all the samples collected is 0.94 phi and the minimum grain size, d10, is 1.3 phi. The mean grain size variations show a general coarsening towards the crest of the dune. However, two different intervals are distinguished. The first interval comprises from the beginning of the transect to meter 120. This interval presents a mean grain size of 1.05 phi, which shows that the sand of this interval is slightly finer than the general mean. The variations in this interval do not manifest an overall trend. Three minimums (coarse grains) at 14, 60, and 120 m are identified. The second interval ranges from meter 120 to the end of the profile. This interval is coarser than the previous one and has a mean grain size of 0.76 phi. It starts with an increase towards finer sand up to meter 125, followed by a continuous decrease towards coarser grains. The sorting oscillates between 0.38 and 1.08, having a mean value of 0.65 which, according to the Folk and Ward (1957) description, corresponds to moderately well sorted sand. The lower the sorting value is, the better the sorting is. In general, it is inversely linear correlated to the mean grain size.



**Figure 4.3:** Statistical results of the transect sampled along profile GWD-08. The samples were collected each 5 cm at a mean depth of 50 cm. Graph **A** shows the mean grain-size in phi units. Graph **B** shows the sorting curve of the investigated sediment samples, based on grain-size classes in phi. The original results are shown by the grey curves. Additionally, in order to eliminate spikes and to enhance the general trends, a 5-point running mean was applied (colored lines). The graphs are correlated to the geometrical interpretation (**C**) showed in figure 4.4 to have an overview of the samples age.

Finer-grained sediments (high values in the mean grain-size variations curve) are better sorted than coarser-grained sediments. Although the general trend is not so pronounced as in the mean grain size, the two intervals observed in the mean grain size variations are also identified in the sorting data. The first interval is slightly better sorted than the second one, with a mean sorting value of 0.63. The three minimums observed in the first interval of the mean grain size variations correspond in this case to three maximums (moderately to poorly sorted sand). The second interval starts with a marked decrease towards well sorted sand and then increases showing a not so well sorted trend. The mean sorting value in this second interval is of 0.66.

#### 4.4.3. Characteristics of wind data

Wind data are plotted in wind-roses diagrams based on daily and weekly means between 1950 and 2003 (Fig. 4.4). Wind-data analysis show that westerly and south-westerly winds prevail. Wind velocities between 6 and 10 m/s predominate. Storms (winds > 12 m/s) occur more often from the West. Comparing both wind roses it is observed that the influence of north-easterly and easterly winds is very weak and of short duration. Therefore, in the weekly means graph they do not represent more than the 1%. For a better observation of the wind-variations trend and in order to remove spikes and single events, a 5-point running mean is applied. This is shown in figure 4.5 by the red line, whereas the grey line represents the weekly means. During the investigated period, the wind speed oscillates between 1 and 14 m/s, with a mean value of 7.1 m/s.



**Figure 4.4:** Wind roses based on daily **(A)** and weekly means **(B)**. The wind dataset provided by the Deutscher Wetterdienst consists of hourly measurements. To analyse the data, daily and weekly means were calculated.



**Figure 4.5:** Weekly wind means (grey curve) between 1950 and 2003, plotted together with a 5-point running mean (red curve). This running mean was applied to eliminate single events and to enhance the general trends.

According to the variations of the wind speed, two different subperiods are identified. The first one covers the period from 1950 to 1962. Here, the wind speed oscillates between 3.2 and 12.6 m/s, and the mean velocity is 6.7 m/s. The second subperiod is from 1963 to 2004, it varies between 1 and 14 m/s, and the mean wind speed is 7.2 m/s. This subperiod starts with a rapid increase of the wind speed, between 1963 and 1967, from 2.5 to 12.2 m/s. The overall trend for the whole studied period shows a slight increase on the weekly wind mean from the first to the second subperiod. Considering the mean grain size,  $d_{50}$ , and the minimum grain size,  $d_{10}$ , the wind necessary to transport the sediment present in the study area is calculated (according to the equations introduced in section 4.3.5). Under dry conditions, winds higher than 6.0 m/s, for the  $d_{10}$ , and higher than 7.1 m/s, for the  $d_{50}$ , are needed to produce sediment transport. On the other hand, under wet conditions, wind speeds higher than 8.7 m/s ( $d_{10}$ ) or than 10.5 m/s ( $d_{50}$ ) are necessary for the sediment transport.

#### 4.5. Discussion

### 4.5.1.Correlation between the sedimentological record and the instrumental data

The sedimentological analyses carried out show that the mean grain size of the collected samples increases towards the dune crest. Two different intervals are identified, separated by an absolute minimum at meter 120. The mean grain size changes from 1.05 phi, in the first interval to 0.76 phi, in the second one. The sorting variations are also characterised by two

intervals, separated at meter 120 of the transect, being the first one better sorted than the second one.

The sediment samples were collected at 50 cm depth. They represent grain-size variations along the lee side of the dune: due to the erosion of sediment on the windward slope, the sediment is transported and deposited on the lee side as the dune migrates. As new sediment is deposited on the lee side, the previous layer will be covered by this new one, and thus, it will be preserved, forming a sedimentological archive of sediment deposited in the past. Studies investigating grain-size variations along dunes are focused on samples collected directly on the surface of the dune (e.g., Barndorff-Nielsen et al., 1982; Watson, 1986; Livingstone et al., 1999; Wang et al., 2003) or on samples collected by sediment traps, to investigate the sediment transport (e.g., Arens, 1996; Lancaster, 2009; Delgado-Fernandez and Davidson-Arnott, 2011). Thus, they can only provide information about the wind conditions occurring at the moment of sampling. Here, it is assumed that each sample represents a specific event, and thus it is representative of a whole slipface.

## 4.5.1.1. Theoretical model for the correlation between grain-size and wind-speed variations

A model based on the relation between wind conditions, sedimentological properties, and the sediment supply is proposed to explain the grain-size distribution observed in the subsurface samples of the studied dune (Fig. 4.6). The studied dune is situated approximately 900 m far away from the coastline. Therefore it does not receive new sediment input and, due to its inland migration, it is characterised by a continuous reworking of the sediment. The dune presents a limited sediment pool of grain sizes, which acts as source area. This source area is characterised by a certain sorting value, in which the sediment sensitive of being removed by winnowing is not present. Besides, regarding the wind conditions in the investigated area, the influence of westerly and easterly winds should be considered. Under low-to-moderate westerly winds, weak erosion will occur on the windward side of the dune. The sediment eroded from the source area will be deposited on the lee side and, since the wind is not so strong, only the fine material available in the sediment pool will be transported, causing a fine and well sorted deposit. On the other hand, if the westerly winds are stronger, they will have a higher capacity of erosion on the windward side and they will be able to transport coarser grains. A mixture of coarse and fine sand will be transported causing a poorly sorted deposit. Easterly winds do not occur often, but they should be taken into account to understand the model

#### 1) Westerly winds



**Figure 4.6:** Proposed model based on the correlation between wind conditions and sedimentological properties to explain the observed grain-size distribution. The study area is a close system characterized by a limited pool of sediments. This limited pool of sediments constitutes the source area. The dashed line represents the initial shape of the dune before suffering the erosion of the wind. If westerly winds prevail (1), it should be considered its intensity. Under weak wind conditions (A), weak erosion will be produced on the windward side of the dune. And due to the low intensity of the wind, only fine material will be transported, thus fine-grained and well-sorted sediment will be deposited. Under strong winds (B), a higher erosion will occur and it will also to transport a mixture of fine and coarse sediment resulting in a coarse-grained and poorly-sorted deposit. On the other hand, if easterly winds occur (2), the erosion will be produced on the lee side and the sediments eroded will be deposited on the windward side of the dune, where they will become part the source area for being reworked by the prevailing westerly winds.

Under its influence, the erosion will be produced on the lee side of the dune and the sediment will be deposited on the windward side. This sediment will become part of the source area, where under westerly winds will be reworked again and it will finally be deposited on the lee side. Hence, due to the minor influence of the easterly winds and due to the continue reworking of the source area, it is assumed that the sediment forming part of the source area represents only westerly winds.

Additionally, comparing the mean grain-size and sorting variations to the wind-speed record, it is observed that the sorting presents more fluctuations than the mean grain size, reflecting better the variations observed on the wind-speed record. Therefore it was decided to use the sorting as a statistical parameter to describe the sedimentological record and to correlate it to the wind-speed record.

#### 4.5.1.2. Correlation between grain-size and wind speed variations

Before comparing the sedimentological record to the wind-speed record, the effect of using the mean value of the wind speed instead of the maximum value as wind-speed record should be investigated. This decision was made assuming that the migration of the dune occurs due to the continuous action of the wind: despite the much larger rates of sand movement under high winds, the small number of hours for which they blow means that, theoretically, these are not the most important in terms of their contribution to sand movement (Sarre, 1989). Northern Sylt is characterised by relative strong winds, as it is observed in figure 4.4. Besides, according to the equations shown in section 4.3.5, under dry conditions, winds of 6 m/s will already move fine sediment, and this value occurs quite often in the study area. Therefore, sediment transport will occur, not only under strong wind events, but also with moderate winds. Additionally, to assure that the mean values are representative of the maximum wind speeds, a bivariate analysis for a specific period (1963-1967) is done to show how they are related (Fig. 4.7). The result shows a linear correlation between both datasets with a correlation coefficient of 0.92. Despite that the highest values present a slightly higher dispersion than the lower values, it is confirmed that the mean values represent the maximum wind velocities.

The sedimentological record cannot be initially correlated to the wind-speed record because the former is an equidistant space-based dataset whereas the latter is a time-based dataset. Besides, considering the age model based on the aerial images, it is observed that different migrating velocities occurred along the studied period (Table 1). This feature is not reflected in an equidistant space-based dataset. Therefore, it is necessary to convert it to a time-based



**Figure 4.7:** Scatter diagram between the mean wind-speed velocities (x-axis) and the maximum wind-speed velocities (y-axis) for the 1963-1967 period. In addition, statistical results are presented with the equation which describes the correlation between both datasets, the coefficient of determination and the residual mean square.

dataset. The software Analyseries (Paillard et al., 1996) is used to perform this transformation.

The transformation is done on the 5-point running mean datasets. The reference points needed are taken from the aerial images and, based on pattern fitting, two additional points are added to improve the age model (Fig. 4.8). These two points correspond to the absolute minimum and a relative maximum observed in both datasets occurring at the same time range. Thus, with this new age model, the space-based sedimentological record is transformed into a time-based record. This new record reaches back to 1907 and can be subdivided into two intervals. The first interval is characterised by cyclic variations in the range of well to very well sorted sediment until 1963, when the absolute minimum occurs. Then, the second interval starts with a rapid increase towards poorly sorted sand, reaching its maximum in 1967, and continues with cyclic variations oscillating around poorly to well sorted sediment until 2003, when the sedimentological record ends. This transformation also allows to cross-correlate the sedimentological record and the wind record. It has a correlation coefficient of 0.52 (Fig. 4.9). The cross-correlation is done after 1950, when the wind record starts. This cross-correlation is subdivided into three intervals: from 1950 to 1962, from 1963 to 1967, and from 1968 to 2003. In general, similar trends are observed in the three intervals: low wind velocities are correlated to low values of sorting and vice versa. However, the subdivision is done based on the degree of correlation. Out of these three intervals, it is the second (1963-1967) the one which presents the better correlation since it is also characterised for having the best age control: three age points are located in this interval.







**Figure 4.9:** Sorting and wind speed correlation between 1950 and 2003 after the improved age model shown in figure 4.8.

The other two intervals, although they show the general trend described before, they also present several periods with the opposite trend: low wind velocities are related to high sorting values, and the other way around. Possible causes evaluated to explain these dissimilarities between the both datasets are the effect of easterly winds, incompleteness of the sedimentological record due to erosion and non deposition, inaccuracies of the age model, and uncertainties of the sampling procedure. Easterly winds represent only a small percentage of the windspeed record as it is shown in figure 4.4. Moreover, easterly events will not be recorded in the sedimentological record since due to its orientation and position in the dune, it can only record westerly events. Thus, the influence of easterly winds is neglected. Sediment gaps have been observed based on the dune architecture (fig. 4.2). Features describing sediment gaps are erosional unconformities and toplap geometries. Erosional unconformities have been observed only before 1944. They are mostly produced by easterly storms. Thus, it is interpreted that after 1944 no strong easterly storms occurred or, if they did, they were too short and they were not recorded in the sedimentological record. On the other hand, toplap geometries are found after 1965. It is observed that where these geometries are present, more sediment is accumulated in the lower part than in the upper part of the dune indicating that some sediment is lost. Even though the position of these gaps in the sedimentological record is identified, is not possible to measure how much sediment was eroded or not deposited. Thus, it should be assumed that the sedimentological record is incomplete causing an undetermined uncertainty. Due to the resolution of the aerial images and due to the digitizing process and the projection of the timelines into the GPR profile, the position of each timeline in the age model has a resolution of ± 1-2 m. Although the sampling step is quite small (5 cm), some uncertainties are associated to the sampling procedure. They come from the fact that under strong wind conditions more sediment will be deposited than under weak wind conditions. Thus, there are more probabilities of sampling the sediment deposited under strong winds, whereas the samples deposited under weak winds might be underestimated. Considering the presence
of these uncertainties, it should be assumed that a correlation point to point is not possible. This is the reason why some periods present no correlation between the sedimentological and the wind records. However, it has been observed that the general trends in both datasets are preserved and that the sedimentological record is a potential new archive of wind-speed variations.

## 4.5.2. Cyclicities

The time series of the sedimentological record as well as of the wind-speed record show cyclic variations. In order to evaluate the cycles present in the data, a wavelet analysis is performed. The procedure described by Torrence and Compo (1998) is applied to the 5-point running mean datasets.

## 4.5.2.1. Space-based cyclicities

In a first step, the wavelet is applied to the spaced-based sedimentological record (Fig. 4.10). The black line in the wavelet power spectrum (WPS) corresponds to the cone of influence, which has a statistical significance of a 95% confidence level. The areas below the cone of influence should be interpreted carefully because they are affected by edge effects, which could lead to a misrepresentation of power magnitude (Torrence and Compo, 1998a). Therefore, only the high-power areas situated significantly above the cone of influence should be trusted. The horizontal high-power areas in the WPS display graphically the period of the cyclicities detected in the dataset. When these areas are averaged the global wavelet spectrum (GWS) is obtained. The GWS provides quantitative information related to the main wavelengths of 1.65, 3.99-5.56, 13.22, and 62.89 m. The 1.65 m cycle shows a patchy pattern along the whole transect presenting a higher power after meter 100. The cycle ranging between 3.99 and 5.56 m appears continuously along the investigated transect, presenting the highest power in the



Figure 4.10: Wavelet analysis for the sorting space-based dataset.

intervals between 5 and 33 m, 51 to 89 m, 115 to 140 m, and 170 to 200 m. The 13.22 m cycle shows its maximum power between meter 20 and 33, 51 to 89 m, and 115 to 140 m. This cycle is also characterised for being completely absent between 150 and 190 m. The last cycle, 62.89 m, is not reliable since it falls quite close to the 95% confidence level. A secondary cycle of 22.24 m is also observed in the GWS, although in the WPS its power is not that strong, in comparison with the other mentioned cycles.

Comparing these results to the migrating velocities given in Table 1 and, considering a mean migration velocity of 4.1 m/yr for the whole studied period, it appears that the 1.65 m cycle is related to biannual changes, the 3.99-5.56 m cycle would correspond to the annual cyclicity, the 13.22 m cycle is associated to a cyclicity of 3 years whereas the 22.24 m cycle would correspond to a 6 years cyclicity. The broad peak given by the annual cyclicity confirms that the dune does not present a constant migrating velocity. The WPS applied to the space-based sedimentological record can also be interpreted as sediment thickness. When the dune moves faster, more sediment will be accumulated, and the annual cyclicity will have a larger length. This will be observed in the WPS as changes in the position of the annual cycle, which changes its position towards higher periods. Thus, changes of the migration rates of the dune can be analysed independently from the aerial images. Accordingly, it is interpreted that the dune migrated faster between meters 5-35, 52-71, 76-99, 116-127, and 170-187.

### 4.5.2.2. Time-based cyclicities.

In order to estimate more accurately the period of the cyclicities observed in the previous section, the wavelet analysis is applied to the time-based sorting series between 1950 and 2003, to cover the same time span than the wind-speed dataset. This wavelet shows that the main cyclicities are of 0.5, 1.1-1.5, 3.6, and 6 yr (Fig. 4.11). The biannual cycle, 0.5 yr appears again as a patchy pattern, showing the strongest power between 1959-1966 and 1988-2003. The annual cycle is present along the whole period, presenting a higher intensity for the following years: 1953-1957, 1960-1964, 1970-1974, 1976-1980, 1982-1988, 1990-1994, and 1996-1999. The 3.6 yr cycle is especially stronger between 1977 and 1996, and the 6 yr cycle is quite constant along the investigated period showing a slightly higher power between 1958-1975 and 1975-1995. The annual cyclicity is given again by a broad peak, oscillating between 1.1 and 1.5 yr, and showing another evidence of the irregular migration velocity of the dune. In general, it is observed that the annual cycle defines a change in sorting for well to poorly to well sorted sediment.



Figure 4.11: Time series of the sorting time-based dataset (A) together with the wavelet analysis (B) between 1950 and 2003.

On a last step, the WPS is applied to the wind-speed dataset, which shows 0.5, 1, 5, and 8.5 yr cycles (Fig. 4.12). The annual cyclicity describes a variation in the instrumental record from low to high to low wind speed. Comparing these cyclicities to the ones obtained in the sedimentological record, it is observed that in both datasets the biannual and the annual cyclicities are present. Besides, the annual cycle in both datasets corresponds with the expected result according to the model presented in section 4.5.1.1: a well-poorly-sorted oscillation is the result of a low-high-low wind-speed cyclicity.



**Figure 4.12:** Time series of the wind-speed record (**A**) together with the wavelet analysis (**B**) between 1950 and 2003.

Regarding the other cycles present in both datasets, it is interpreted that the 3.6 and 6 yr cycles observed in the sedimentological record are related to the 5 and 8.5 yr cycles observed in the wind-speed record. This premise is done by assuming the presence of uncertainties in the sedimentological record derived from the age model in the process of converting the sedimentological record from a space-based to a time-based dataset, and due to gaps present in the sedimentological record. These gaps are caused by non-depositional periods, erosional unconformities, and by the fact that the sedimentological record reflects only sand deposited by strong winds. If these uncertainties are considered then, the 3.6 and 5 yr cycles found in the sedimentological record would be larger and thus, could be related to the 5 and 8.5 yr cycles present in the instrumental record.

Assuming that the cyclicities observed in the wind record are reflected in the sedimentological record, the process that has triggered those cyclicities should be analysed. Considering the cycles observed in the wind-speed record of 6 and 8.5 yr, it is considered that a possible process behind these cycles could be related to the North Atlantic Oscillation (NAO).

The NAO is a climatic phenomenon which refers to changes of atmospheric mass between the Arctic and the subtropical Atlantic, and swings from one phase to another producing large changes in surface air temperature, winds, storminess, and precipitation over the Atlantic as well as adjacent continents (Hurrell and Deser, 2009). The changes in the NAO index are determined from the difference in sea-level pressure between winters with an index value greater than 1.0 and those with an index value less than 1.0 (Hurrell, 1995). The NAO index gets positive, in a stronger phase with a high pressure gradient, and negative, in phases with a weaker gradient. A positive NAO index causes stronger than normal westerlies, high precipitation, and mild temperatures in Northern Europe during winter. The changes in circulation are in an interannual to decadal timescale. Therefore, the wavelet analysis of the NAO index can show whether the timescale of the changes in circulation is similar to the timescale of the variations reflected in the wind-speed and sorting wavelets. The selected NAO index is the one defined by Hurrell (1995). This index measures the difference in sea-level pressure in winters between Lisbon (Portugal) and Stykkisholmur (Iceland). In order to compare the NAO dataset to the sedimentological and the wind records a 5-point running mean is applied to the monthly NAO index between 1950 and 2003 to execute the wavelet power analysis. The wavelet spectrum shows cycles of 0.5, 2.3, 5.5, and 9.3 yr (Fig. 4.13). The NAO index represents sea-level pressure differences on a regional scale whereas the instrumental data investigated is on a local scale. Thus, it is not possible to assure that the NAO is related to the wind and sorting

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variations. However, due to the similarities on the cyclicities observed, the NAO is proposed as a possible trigger of the wind and sorting cyclicities.



**Figure 4.13:** Time series of the monthly NAO index (**A**) together with the wavelet analysis (**B**) between 1950 and 2003.

# 4.5.3. Reconstruction of wind-speed variations in the past. A new climate archive.

Results shown in the previous section demonstrate a correlation between the sediment samples collected alongside the dune and the wind-speed variations recorded in the meteorological station situated nearby the study area. This correlation suggests that the investigated dune is a potential new archive for reconstructing wind-speed variations in absence of instrumental data. The comparison between the sedimentological record and the wind-speed record shows the evolution of the local wind speed after 1950. Despite the uncertainties derived from the age model, it is observed that, generally, the periods with stronger wind conditions are reflected on poorly sorted material whereas the periods with moderate wind conditions are related to well sorted samples.

## 4.5.3.1. Bivariate analysis between 1963 and 1967

In order to reconstruct the wind speed prior to 1950, the period between 1963 and 1967 was investigated by applying a bivariate analysis. This period was elected because it presents the best age control and thus, it is expected to show the best relation between the wind and sorting

datasets. The datasets consist on weekly means with a 5-point running means (Fig. 4.14). The distribution of the points in the bivariate analysis reflects three possible wind regimes.



**Figure 4.14:** Bivariate analysis between the sorting record (x-axis) and the wind-speed record (y-axis). The data plotted corresponds to the period 1963-1967. The analysis identifies three different wind regimes which are depicted by the different colors.

On the one hand, sorting values lower than approximately 0.65 are related to wind velocities oscillating around 6 and 7.5 m/s. However, they are broadly dispersed and they do not show a clear correlation. On the other hand, sorting values higher than 0.65 are subdivided into two groups. In the first subgroup the sorting values are related to wind velocities oscillating between 6 and 9.5 m/s. It shows a linear trend which fits with the model proposed in section 4.5.1.1: the higher the wind velocity, the poorer the sorting is. The second subgroup is formed by a low number of points with high sorting values, but low wind velocities (between 5 and 6 m/s). The low number of points present in this group suggests that they are related to the uncertainties derived from the age model resolution, the incompleteness of the sedimentological record, and/or to short storm events that cannot be properly recorded. It should be noted that the wind-speed record is formed by weekly means, and thus, if a short storm event occurs, it will be attenuated by the mean.

The bivariate analysis shows that between 1963 and 1967 the relation between wind and sorting describes two different wind regimes and that it is related to the occurrence of strong events. Based on the data distribution, a strong event takes place in days with wind velocities higher than 8 m/s. To reduce the influence of the uncertainty given by the age model and to evaluate the whole stormy period, the number of events higher than 8 m/s was counted annually between June of 1963 and May of 1968. If this is plotted against the annual mean of

sorting, it is observed that the years with less number of strong events are related to sorting values lower than 0.65, whereas when the sorting is higher than 0.65 more strong events occur (Fig. 4.15). Therefore, it was decided to use this value to distinguish between both subgroups and to define two functions to describe the relation between the sorting and the wind speed (Fig. 4.16). Assuming that these functions can be extrapolated to the entire studied period and then, applied to the sorting data before 1950, it would be possible to reconstruct the wind-speed variations in absence of instrumental data.

By adding a linear fit, it is observed that, whereas the group with sorting values lower than 0.65 shows a trend opposite to the one expected in the model, the group with a sorting higher than 0.65 fits with the model. It is assumed then, that the strong events with high sorting values are better recorded than the weak-to-moderate events. Strong winds are expected to transport more sediment than weak or moderate winds. Thus, a thicker layer will be deposited and it will have more possibilities of being recorded. This is also confirmed by the high dispersion and lack of correlation observed in the group with low sorting values. Therefore, it is assumed that only wind events related to sorting values higher than 0.65 can be reconstructed. The equation describing this group is

$$y = 17.2366x - 4.2556$$



where y is the reconstructed wind and x the sedimentological record represented by the sorting.

**Figure 4.15:** Scatter plot between the annual sorting mean (x-axis) and the number of strong-wind events per year (y-axis). It is considered strong events those with mean wind velocities higher than 8 m/s.

# 4.5.3.2. Wind speed reconstruction based on a sedimentological record

If the previous equation is applied to the entire sedimentological record, the variations of the mean wind speed before 1950 can be reconstructed back to 1907 (Fig. 4.17). The reconstruction shows that the mean wind velocity after 1950 was higher than before 1950. According to the presence of gaps related to low-to-moderate winds, it is also interpreted that they occurred more often during the first part of the 20th century. If the reconstruction is analysed in detail, it can also be observed that the periods with stronger winds occurred at the end of the first decade, beginning and end of the second decade, second half of the 1930s, mid-to-late 1940s, mid-to-late 1950s, and finally, the period which goes from the mid 1960s to 2003. In contrast, the calmest periods were the mid 1910s, the 1920s, the beginning of the 1930s, late 1940s to beginning of the 1950s, and beginning of the 1960s.

The comparison with the instrumental record can only give an idea of the wind variations occurring after 1950. For the period between 1950 and 2003, it is observed that, even though the absolute values are not the same, in general, similar trends are preserved, i.e., the absolute minimum occurring around 1963 coincides with a gap in the reconstruction and then, it is followed by a marked increase on the wind speed. Thus, to demonstrate the veracity of the reconstruction prior to 1950, it is compared to previous studies investigating wind variations



**Figure 4.16:** Bivariate analysis of the sorting record (x-axis) and the wind-speed record (y-axis) between 1963 and 1967 after the differentiation of two subgroups according to the number of strong events. Sorting values lower than 0.65 describe low-moderate events (dark-blue dots), whereas sorting values higher than 0.65 depict better strong events (light-blue dots). In addition, statistical results for both subgroups are presented with the equation which describes the correlation between both datasets, the coefficient of determination and the residual mean square.

occurring in the last century. Most of these previous studies deal with variations of storminess. Therefore, it should be remarked that the reconstruction presented in this study shows variations of the mean wind speed. This means that if an increase in the mean wind velocity is observed, an increase in storminess cannot be necessarily inferred. Nevertheless, an increase in storminess will be the result of an increase in the intensity of the wind speed. Thus, in order to investigate general trends of wind speed variations, these kind of studies can be used for comparison.

Based on observations, Lamb (1991) presented a historical investigation of storms occurring in the North Sea, British Isles, and northwest Europe. The ones which affected the German coast, and thus, could have affected the coast of Sylt, are plotted in fig. 4.17. Some of the storms, as the ones occurring in 1916, 1962, 1967, 1968, 1973, and 1976, could be associated to peaks related to high wind velocities. However, due to the resolution of the reconstruction, it is not possible to assure that these single events are really reflected on the data. De Kraker (2002), based also on documentary sources, created time series of storms, storm surges, and high floods for the period of AD 1500 to 2000 for the British, Danish, and German coast. He concluded that there was a considerable increase in the number of storm surges and consequently in storminess during the second half of the 20th century on the Dutch coast and the British Isles as well as an increase on the sea level in the German coast. If the number of gales Beaufort 10 to 12 used as indicator of storminess is plotted between 1910 and 2000, an increase in storminess in the Dutch coast starting in 1970 is observed (de Kraker, 2005). Cardone et al. (1990) investigated wave observations obtained from ships. He also found that pre-1950 winds appear to be weaker than the post-1950 winds. However, the data used in all these studies might suffer of the inhomogeneity problem due to changes in the observation practices and/or changes in the method of measuring, e.g., increase in the use of anemometers after certain period.

Nowadays, the most reliable data to assess past storm activity is obtained from the calculation of geostrophic winds based on triangles of pressure readings (Schmidt and von Storch, 1993; Krueger and von Storch, 2011). Geostrophic winds are winds blowing parallel to the isobars which are computed from surface air pressure readings and that represent the ground-level wind speed. The benefits of using this kind of data rely on the fact that the instrument used for measuring air pressure, mercury barometers, has not changed for more than 100 years. Thus, the measurements do not present substantial inhomogeneities and can cover long periods, which is a requirement for identifying trends in climate (Schmidt and von Storch, 1993).

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Previous studies dealing with calculation of geostrophic winds (The WASA Group, 1998; Alexandersson et al., 2000; Matulla et al., 2008), as well as those dealing with simulated data (Weisse and Plüβ, 2006; Donat et al., 2011) show a positive trend in storminess from the 1960s to the 1990s. This positive trend started from particularly calm conditions and was broken by the middle of the 1990s. Afterwards, the levels of storminess are comparable to those of the turn from the 19th to the 20th century. Additionally, some of the studies also observed phases of high storm activity during the first decades of the 20th century (Matulla et al., 2008; Donat et al., 2011). Even though these studies are done on a regional scale and thus the observation of the exactly same variations cannot be expected, general trends are observed, especially the marked increase occurring in the late 1960s. Other features observed in those previous studies as well as in the present reconstruction are the relative high values at the beginning of the century, the minimum in the early 1960s, preceding the increase of the mean wind velocity, and the minimum in the mid 1990s.

All these observations and similarities confirm the potential of migrating dunes for reconstructing wind-speed variations in absence of instrumental data, despite that it could be argued that the datasets used for this reconstruction present several uncertainties. However, the comparison of the reconstructed wind variations with other proxies, such as geostrophic winds, or observations shows similar trends. Although it is not possible to identify single events, the general trends on a decadal timescale are present. Such results have never been found on a geological record.

### 4.6. Summary and conclusions

Linking sedimentological, meteorological, and GPR data allows developing a model to explain the correlation between a sedimentological record, obtained from a migrating dune, and windspeed variations. Thanks to this model it is possible to reconstruct wind-speed variations in absence of instrumental data, confirming the potential of migrating dunes as climate archives.

The correlation between the sedimentological record and the wind-speed variations done between 1950 and the end of 2003, shows that generally, under weak conditions, only the finest material is transported. Thus, the obtained deposit will be well sorted. When stronger winds occur, both fine and coarse sediment will be transported, leading to a heterogeneous and worse sorted deposit. A direct correlation between the sedimentological and the windspeed records shows that the correlation coefficient obtained is 0.52. This value, although showing an acceptable correlation, evidences that a correlation point-to-point is not possible to obtain. The absence of a direct point-to-point correlation is a result of the uncertainties derived from the incompleteness of the sedimentological record due to phases of erosion and non deposition, inaccuracies of the age model, and uncertainties of the sampling procedure owing to the impossibility of sampling short events. However, it should be marked that, despite the presence of these uncertainties, the general trends between both datasets are preserved.

The potential of this record as climate archive is also observed in the presence of cyclicities. Cyclicities of the same order are observed in both datasets. In both cases, biannual and annual cyclicities are observed, describing a change in the sedimentological record from well to poorly to well sorted sediment and a variation in the instrumental from low to high to low wind speed. The results also show a 3.6 and a 6 yr cycle in the sedimentological record, and a 5 and 8.5 yr cycle in the wind-speed record, which are interpreted to be correlated. Thus, it is assumed that the cyclicities observed in the sedimentological record reflect the ones observed in the wind record. As possible trigger of these cyclicities, the NAO is proposed.

Due to the similarities observed between the sedimentological and the wind-speed records, a function to describe its relationship is defined allowing to reconstruct the wind-field variations in absence of instrumental data back to 1907. The reconstruction manifests that the decades with stronger wind conditions were the end of the first decade, beginning and end of the second decade, second half of the 1930s, mid-to-late 1940s, mid-to-late 1950s, and finally, the period which goes from the mid 1960s to 2003. After comparing the reconstruction with other reliable data, it is concluded that general trends on a decadal timescale can be reconstructed.

## **Chapter 5**

# **Concluding remarks and outlook**

## 5.1. Conclusions

The aim of this study was to decipher a new archive of temporal wind-field variations recorded in the sediments of a migrating dune. The main outcome of this study is the following:

• Geometrical features as indicators of particular wind conditions have been identified.

 Migration rates variations depend on the annual precipitation and the occurrence of westerly winds blowing above a certain threshold velocity.

• The sedimentological record reflects cyclicities observed in the wind-speed record.

• The approach effectively reconstructs past wind-speed variations on a decadal timescale, based on a sedimentological record.

The reconstruction of the wind-speed variations in absence of data was successfully achieved by the following steps: (1) Implementation of an age model based on OSL dating and aerial imagery; (2) Investigation of the geomorphological development of the dune as well as of the internal architecture; (3) Comparison of a sedimentological record, based on granulometric measurements of approximately 5000 sediment samples, and a meteorological record, based on instrumental measurements of wind speed to identify cyclicities and a mathematical function which describes their relationship.

Since the sedimentological record is a space-based dataset, an age model is required for age assignment. OSL dating has proved to be a powerful tool to date very young sediments (<100 years). However, due to low signal-to-noise ratio of the natural OSL signal, thermal transfer, and small residuals due to insufficient resetting of the luminescence signal, it can still constitute a challenge. Thus, a comparison with a high-resolution independent age model based on aerial images was done to test the suitability of this method. The results show the benefit of using

the early background (EBG) approach instead of the late background (LBG) approach: five of the oldest samples agreed with the independent age model and the thermal transfer was reduced. An overestimation on the six youngest samples remains, despite this improvement. This overestimation is attributed to a small thermal transfer and an incomplete bleaching in the medium and slow OSL component, which cannot be removed by the EBG approach. In order to quantify this residual dose, it is recommended to use the modern analogue approach, especially in cases when no independent age model is available.

Knowledge of the internal geometry and the morphological evolution of the dune are required for a proper correlation between the sedimentological record and the meteorological data. The investigation based on observations of the aerial images revealed that the dune changed from a transverse to a parabolic dune between 1958 and 1965. This transformation occurred due to a reduction of sediment supply and an increase of the vegetation cover, as the dune migrated inland. The interpretation indicates that the increase in vegetation cover is related to an increase in annual precipitation after 1964. Nevertheless, anthropogenic influence causing the increase in vegetation cannot be excluded. Regarding the internal architecture of the dune, a change from tabular to convex foreset geometry occurred after 1965 reflecting the geomorphological change. Additionally, it was found that internal architecture elements reflect specific wind conditions. This is the case for erosional unconformities and toplap geometries. Erosional unconformities can only be formed during long-lasting easterly winds able to erode the lee side of the dune during its continuous migration towards the east. The erosional unconformities appear only in the older part of the dune, dated to have occurred around the end of the 1930's and early 1940's, coinciding with a period of strong and long-lasting easterly winds. Therefore, erosional unconformities can be used to identify periods of strong easterly winds. In this investigation, toplap geometries define sediment packages having a wedge shape. These wedge shapes reflected a higher sediment accumulation in the basal part of the dune than in the upper part. Thus, they had to be caused by a process able to produce sediment accumulation only in the basal part of the dune. It is then interpreted that they are related to the occurrence of cross-winds. Therefore, toplap geometries defining sediment packages with a wedge shape can represent periods of higher wind direction variability. Based on the aerial images, it was shown that the migration velocity has increased between 1936 and 2009 due to the reduction of the dune area. Considering the migration rates observed in the periods defined by the aerial images, it was found that its variations are highly dependant on the annual precipitation and on the occurrence (number of days per year) of westerly winds higher than 3 Beaufort. According to this, three different migration rates can be distinguished: low (2.7 m/yr), medium (4.2 m/yr), and fast (5.1 m/yr). Low migration rates are the result of a combination of a high annual precipitation (> 700 mm/yr) and a medium occurrence of westerly winds above 3 Beaufort (~ 200 days/yr). When the annual precipitation present values of approximately 650 mm/yr and the occurrence of westerly winds is lower than 200 days/yr, medium migration rates occur. The highest migration rates are found when the annual precipitation is approximately 700 mm/yr and the occurrence of westerly winds above 3 Beaufort increases (>200 days/yr).

The correlation between the sedimentological and the wind-speed record showed that, even though a point-to-point correlation is not possible to observe, in general, fine and well sorted sediment was deposited under weak wind conditions, whereas coarse and worst sorted sediment was deposited under strong wind conditions. A wavelet analysis was applied revealing a biannual and an annual cyclicity expressed by change in sorting from well to poorly to well sorted sediment in case of the sedimentological record, and a change in wind speed from low to high to low wind speed, in the wind-speed record. This reflects that the cycles observed in the sedimentological record were caused by the variations of the wind speed. In addition, a 3.6 and a 5 yr cycles in the sedimentological record, and a 6 and a 8.5 yr cycles in the instrumental record were also identified. Despite the fact that these cyclicities present different wavelengths, it is interpreted that they are correlated due to similarities found between the sedimentological and the instrumental records and considering the uncertainties derived from the age model resolution, the sampling procedure, and the incompleteness of the sedimentological record. Taking into consideration the periods of the cycles, the NAO was proposed as a possible trigger of these cyclicities. In order to reconstruct the wind-speed variations based on the sedimentological record, a function describing the relation between both datasets was defined. Applying a function which describes this correlation to the entire sedimentological record it is possible to reconstruct the wind-speed variations higher than 7 m/s back to 1907 with a decadal resolution. Besides, comparison of trends described by the reconstruction with trends described in previous studies using observations or geostrophic winds, shows the suitability of the reconstructed data.

## 5.2. Outlook

This study successfully revealed an archive of temporal wind-speed variations recorded on the sediments of a migrating dune. Despite obtaining positive results, this study brings into question possible future research.

The ages of very young samples obtained from OSL dating present an overestimation attributed

mainly to homogenously poorly bleaching in the medium and slow OSL component. Future attempts to avoid the overestimation should focus on extracting only the fast OSL component from the net OSL, since it is the component that bleaches the fastest. This could be done by OSL signal de-convolution or Linear Modulated (LM) OSL measurements. Because the OSL dating has successfully dated the oldest samples, this method should be used when investigating climate archives in older dunes.

This investigation simplifies the correlation between sedimentological and wind records, assuming that one sediment sample is representative of a whole slipface since it was deposited by a certain wind speed. However, wind speed can vary throughout the day. To improve the resolution achieved in this study, it is recommended to use sediment traps on the lee side of the dune to determine the wind speed required to deposit certain sediment.

The integrated methodology applied in this research has been used in one dune. It would be very interesting to extend the methodology to other active and inactive dunes of surrounding areas, e.g., active dunes at the coast of Denmark or the inactive dunes of Listland, to test if similar variations are present. This could help to both improve the method and find out if the NAO variations are really reflected in the sediment of the dune. Besides, sampling inactive dunes would provide a dataset of wind-field variations for a time period not covered by instrumental data.

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