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Department of Geology

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Front cover: Road cut through an aeolian dune at Skattungheden, Dalarna County, Sweden

Back cover: The author taking OSL samples. Image courtesy of Helena Alexanderson

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Abstract

In the Swedish inland there are aeolian deposits present, ranging from scattered single dunes to dune fields of more than 10 km^2. These dune fields often pass unnoticed since they presently are covered by vegetation. However, they contain a rich palaeoenvironmental archive. Only a few research papers have been published regarding these aeolian deposits during the last 90 years. The primary scope of this thesis has been to determine why these dunes formed, when they formed, and what they can tell us about the environment during their formation. The results from these investigations are presented in four research papers.

The shape and orientation of a dune is determined by the local environment during its formation, such as the abundance of sediment available for entrainment by the wind, groundwater table fluctuations, changes to precipitation and temperature, presence/absence of vegetation, mode of the wind et cetera. By determining the type of dunes it is possible to determine the local environment during their formation. If one also can determine when these dunes formed and stabilised one can determine the palaeoenvironment, and in extension the palaeoclimate, during a specific time period.

In this thesis, new findings are presented regarding the geomorphology, geochronology and palaeoenvironment of a number of dunes and dune fields in south and central Sweden, based on state-of-the-art methods, such as LiDAR (light detection and ranging) based remote sensing and optically stimulated luminescence dating. The previous hypotheses concerning the formation of these dunes have also been evaluated.

The findings show that the dunes of central Sweden are primarily of a transverse type, i.e. their dune ridges are transverse to the dune forming winds and they were formed in a setting devoid of vegetation and with an abundance of sediment. The primary dune forming winds for these transverse dunes appear to have been north-westerly and westerly winds. The investigated dunes further to the south show signs of having been reworked after their initial formation and are often of a parabolic type, i.e. curved/crescentic in shape with their arms facing upwind. These dunes have been described as strongly linked to the presence of vegetation, and can often be considered secondary dune forms. These more southern dunes appear to also mainly have been formed by north-westerly and westerly winds, although they display a bigger scatter in wind directions than the more northern dunes.

The luminescence ages suggest that most of the dunes formed during the early Holocene, and later events of sand drift have been uncommon with only minor impact on the dune morphology. There seems to have been a primary dune stabilisation phase ~10-9 ka, irrespective of the latitude of the dune fields. This means that some dune fields formed close after local deglaciation, while others formed millennia later. This suggests that dune formation and dune stabilisation of central Sweden have been controlled by regional environmental conditions. Extremely low lake levels in southern and south-central Sweden 10.5-9.5 ka BP in conjunction with an unstable climate during early Holocene probably delayed dune stabilisation by vegetation. After the vegetation had stabilised the dunes, they became much more resilient to further fluctuations in the climate.

Key words: aeolian deposits, inland dunes, LiDAR, DEM, GIS, luminescence dating, Holocene, Sweden

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“People look down on stuff like geography and meteorology, and not only because they’re standing on one and being soaked by the other. They don’t look quite like real science. But geography is only physics slowed down and with a few trees stuck on it, and meteorology is full of excitingly fashionable chaos and complexity.”

-Feet of Clay-
Terry Pratchett

Contents

List of Papers

This thesis is based on the four papers below.

Paper I

Alexanderson H & Bernhardson M. 2016. OSL dating and luminescence characteristics of aeolian deposits and their source material in Dalarna, central Sweden. Boreas 45, 876-893. DOI: 10.1111/bor.12197. Reprinted with permission of John Wiley and Sons.

Paper II

Bernhardson M & Alexanderson H. 2017. Early Holocene dune field development in Dalarna, central Sweden: A geomorphological and geophysical case study. Earth Surface Processes and Landforms 42, 1847-1859. DOI: 10.1002/esp.4141. Reprinted with permission of John Wiley and Sons.

Paper III

Bernhardson M & Alexanderson H. in press. Early Holocene NW-W winds reconstructed from small dune fields, central Sweden. Boreas. DOI: 10.1111/bor.12307. Reprinted with permission of John Wiley and Sons.

Paper IV

Bernhardson M, Alexanderson H, Björck S & Adolphi F. manuscript. Sand drift events and surface winds in south-central Sweden: From the deglaciation to the present. To be submitted to Quaternary Science Reviews.

Acknowledgements

The data concerning previously mapped aeolian deposits and other geological data was provided by the Geological Survey of Sweden (SGU); either through geodata.se (Sweden's implementation of the EU directive *Inspire*) or from SGU directly. The LiDAR data was provided by Lantmäteriet, also through geodata.se.

The majority of the project *Aeolian activity in Sweden: an unexplored environmental archive*, which this thesis is part of, was funded by SGU (grant no. 61-1555/2012). The salary for my PhD position was funded by the Faculty of Science, Lund University. Funding for various activities was provided by Helge Ax:sons stiftelse, the Royal Physiographic Society of Lund, the Royal Swedish Academy of Sciences and the Faculty of Science, Lund University.

I wish to thank my supervisors Helena Alexanderson, Svante Björck and Per Möller. You have offered valuable comments on many aspects of my PhD project; everything ranging from feedback on manuscripts to suitable sites for fieldwork. Especially my main supervisor Helena deserves my most sincere gratitude; the aeolian research group was a new group when I started, and we have often been one of the smallest groups at the Department of Geology at Lund University, for most of the time consisting of only us two. The project's outline was a very ambitious one, especially when all participants had other engagements at the department. Nevertheless, after we divided the focus of the project between us we progressively moved from a supervisor – student workgroup to something that felt like a research group, with each member contributing with their specific expertise. I am confident that these years as your PhD student have prepared me well for a future career in academia.

Thanks go to co-authors and other people that have helped me during my PhD: Florian Adolphi, for help with statistics and Matlab, your input increased the quality of my papers; Leif V. Jakobsen, for GPR measurements in the field; Edyta Kalińska-Nartiša and Sara Florén for help during fieldwork and processing of luminescence samples; Johanna Anjar for help during fieldwork; Gustaf Peterson and Colby Smith for agreeing to meet me during my visit to SGU in Uppsala and discuss my remote sensing data; and Megan Allington, for proofreading my manuscripts.

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To the rest of the staff at the Department of Geology I am grateful for all help during my PhD, especially members of the Kansli that made the bureaucracy bearable.

Special thanks go to family and friends, you were always polite (well, most of the times) to at least pretend you were genuinely interested in my work. Special mentions go to Emil & Jossan, for caring and surprising with gifts even though we live in different parts of the country; Johannes, for always making me want to go to work; lastly, my mother, for always supporting me.

Scope of thesis

The aim of this thesis has been to investigate the aeolian deposits of central Sweden, especially inland sand dunes, to evaluate their potential as a palaeoenvironmental archive. This can be subdivided into a number of research questions:

- Why did the sand drift events occur that allowed the formation of aeolian dunes in central Sweden, and what can they tell us about past wind patterns and the palaeoenvironment?
- When did aeolian events occur in central Sweden, and were these events of sand drift occurring repeatedly throughout the Holocene or were they limited to certain periods?
- What kind of information concerning the palaeoenvironment can be gained by using state-of-the-art methods for geomorphological and geochronological investigations compared with previous research?

Introduction

Wind is a strong geomorphological agent in shaping the landscape. What usually comes to mind when people think about sand drift are images of huge sandstorms (which often are not mainly made up of sand, but of finer particles) in the major desert areas of the world, such as the Sahara. Less well-known is the fact that many of the world's temperate to subarctic zones contain more or less substantial aeolian, i.e. windblown, deposits, such as the European sand belt (e.g. Isarin *et al.*, 1997; Kasse, 1997, 2002; Koster, 1988; Tolksdorf and Kaiser, 2012), the Great Plains of North America (e.g. Ahlbrandt *et al.*, 1983; Halfen *et al.*, 2016; Muhs and Wolfe, 1999) and scattered inland dunes in Fennoscandia (e.g. Bergqvist, 1981; Högbom, 1923; Klemsdal, 1969; Matthews and Seppälä, 2014). Many of these aeolian deposits go unnoticed in Sweden since they are not active, but instead covered by vegetation (Fig. 1; e.g. Bergqvist, 1981; Seppälä, 2004). These dune fields are thought to have formed when the climate was quite different from the present, during the last deglaciation. At that time, many areas were devoid of vegetation and covered by glaciofluvial and glaciolacustrine sediments deposited during the Weichselian (Seppälä, 2004). These uncovered sediments, in conjunction with winds stronger than the

Fig. 1.
Road cut through an aeolian dune at Skattungheden, Dalarna County, Sweden.

Box 1. Aeolian sand dune research

At first glance aeolian sand dune research might seem like a niche scientific subject, with little to no relevance for society. This is however not correct; many different sciences and parts of society are affected by aeolian processes. As highlighted by Pye and Tsoar (1990), aeolian sand dune research is important for a variety of different topics; such as agriculture, soil science, ecology, engineering and geomorphology (Fig. B1). Engineering applications have mainly focused on dune stabilisation and preventing coastal erosion (Pye and Tsoar, 1990); and aeolian erosion has not only historically, but also recently caused damage to agriculture, with large economical losses (e.g. Bärring *et al.*, 2003; Nordstrom and Hotta, 2004). For earth sciences the interest for aeolian sediment and landforms has covered many topics, everything from classification of landforms to using aeolian deposits as a palaeoenvironmental archive for changes in surface winds et cetera (e.g. Bernhardson and Alexanderson, 2017; Pye and Tsoar, 1990; Seppälä, 2004; Wolfe and Hugenholtz, 2009).

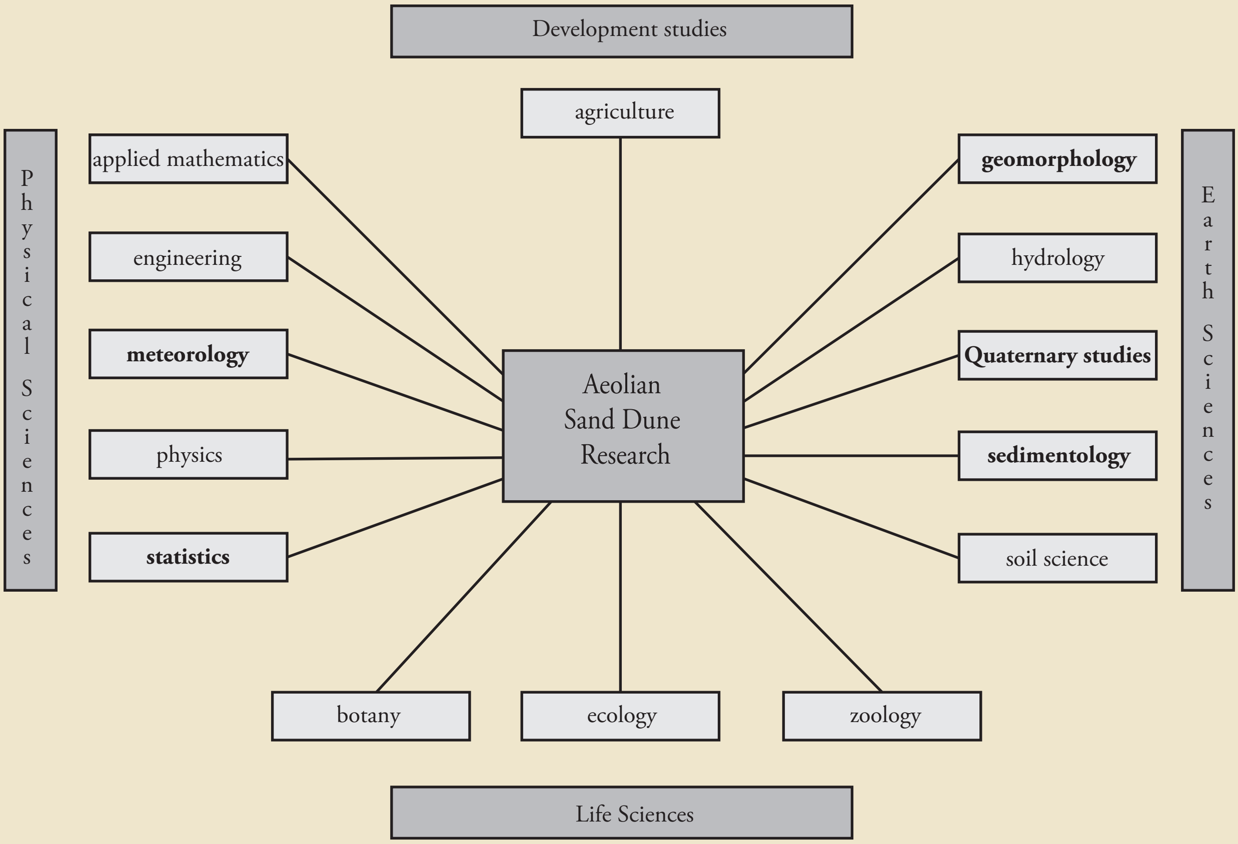

Fig. B1.
Examples of different scientific disciplines concerned with aeolian sand dune research. Disciplines important for this thesis are written in bold. Modified from Pye and Tsoar (1990).

present (Seppälä, 2004), made an ideal environment for sand drift and dune formation. The dunes thus form a palaeoenvironmental archive that can tell us about the past climate and environment.

Past climate change is of importance to be able to understand our planet's history, but also to be able to predict what might happen in the future; since climate models base their assumptions on the palaeoenvironment and/or try to determine their accuracy by modelling past climate fluctuations (cf. Hughes *et al.*, 2016; Svendsen *et al.*, 2004). Understanding what has happened in the past is thus of importance to be able to predict what might happen in the future.

Sand dunes do not only reflect the environment during their primary formation, but can also register events of reactivated sand drift, from large events reshaping most of the dunes, to small events not causing any noticeable changes to the dune morphology. These reactivation events may be due to a number of different reasons; anthropogenic or natural forest fires, marine transgressions or regressions, groundwater table variability, changes to intensity and mode of wind and wind patterns, changed land use practices or changes in temperature and precipitation (Bärring *et al.*, 2003; Käyhkö *et al.*, 1999; Pye and Tsoar, 1990; Seppälä, 2004). The potential of preserved changes in wind patterns is especially interesting for these formerly glacial and periglacial areas since the large continental ice sheets of the last glaciation are thought to have had a profound impact on regional wind patterns (Thorson and Schile, 1995). Aeolian deposits are thus able to record short term environmental changes as well as more long term trends in climate. Despite their value as a palaeoenvironmental archive the aeolian dunes of the Scandinavian inland have attracted modest attention from the scientific community. This is visualised by Lancaster *et al.* (2016) where very little data is available from Scandinavia in the INQUA Dune Atlas (Fig. 2). A likely reason for this is that the aeolian deposits of Scandinavia are rather scarce compared to other areas of the world (Högbom, 1923), and thus have been considered to be of low priority. More attention has been given to coastal dunes, since coastal erosion is often considered to be of greater concern for society (e.g. Doody, 1991; Hanson and Lindh, 1993). Most of the aeolian dune research in Sweden took place in the 1920s and 1930s, with quite conflicting ideas of the formation of Sweden's two largest dune fields; Bonäsheden and Brattforsheden (cf. Enquist, 1932; Högbom, 1923; Hörner, 1927; von Post, 1934). Needless to say, Sweden still has quite a few riddles to solve concerning its aeolian deposits. To diminish this blind spot in the scientific literature I and my co-workers have revisited these dune fields and a number of other dune fields in the Swedish inland (Fig. 3). Using state-of-the-art methods to determine the dunes' morphology and age I aim to validate or disprove the hypotheses of previous researchers (e.g. Enquist, 1932; Högbom, 1923; Hörner, 1927; von Post, 1934), and get a better understanding of the formation of the aeolian dunes in Sweden.

Climate change during late Pleistocene and Holocene

To understand these relict sand dunes scattered across the world, it is important to understand how the climate was during their formation, and what events that enabled their formation and subsequent stabilisation by vegetation. During the last glacial maximum (LGM, 26.5-19 ka) large parts of the world's continents were covered by huge ice sheets (Clark *et al.*, 2009). Due to the immense size of these ice sheets anticyclones formed above the ice masses, which had a profound impact on the regional wind patterns (c.f. COHMAP Members, 1988; Thorson and Schile, 1995), causing clockwise winds emanating from the ice sheets in the northern hemisphere (COHMAP Members, 1988). For northern Europe, this means that areas that today are largely affected by the westerlies (Bärring *et al.*, 2003), were instead affected by more north-easterly winds (cf. Enquist, 1932). Outside of the ice sheets' limits large barren areas formed, where fine particles such as silt was deposited as loess across, for example, west and central Europe and North America (Koster, 1988; Thorson and Schile, 1995). As mentioned previously, the winds during the late Pleistocene were

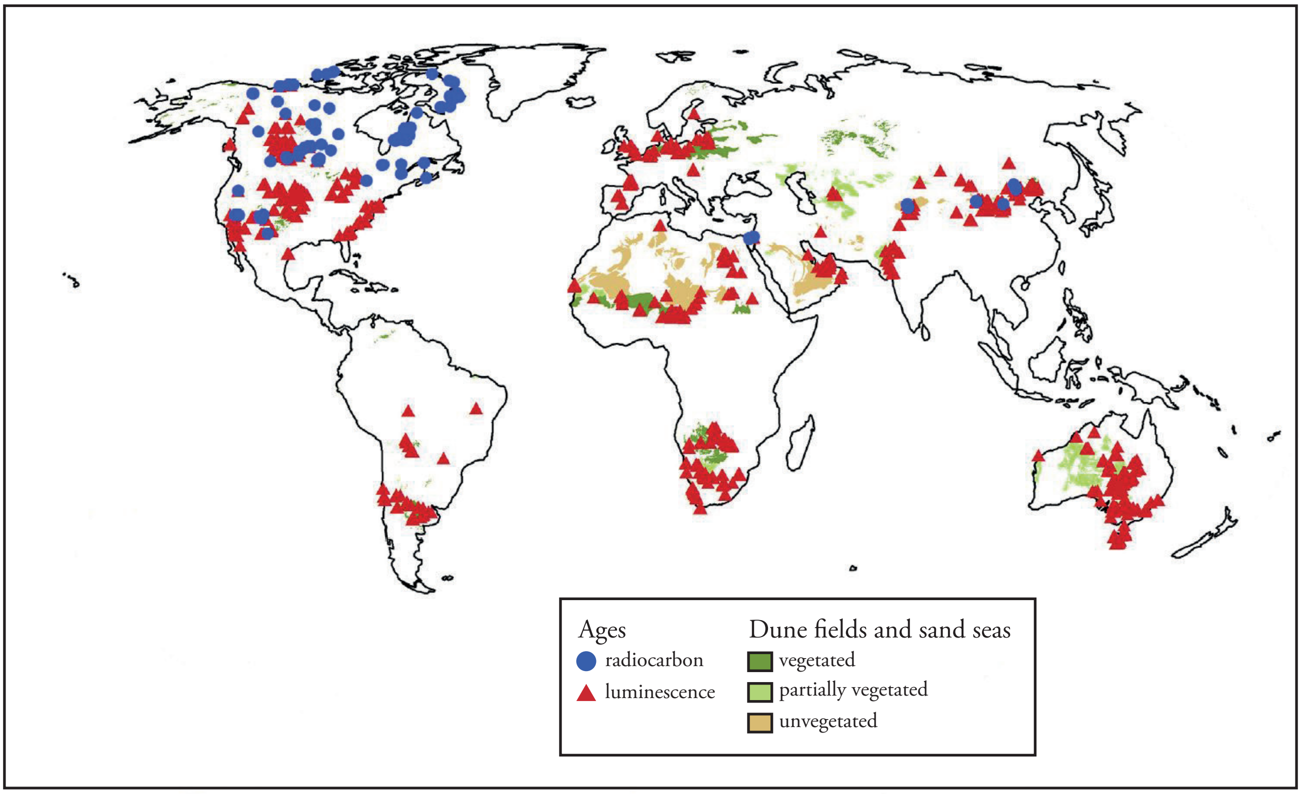

Fig. 2.
The global distribution of aeolian deposits and retrieved luminescence and radiocarbon ages from said deposits in the INQUA Dune Atlas. Modified from Lancaster *et al.* (2016).

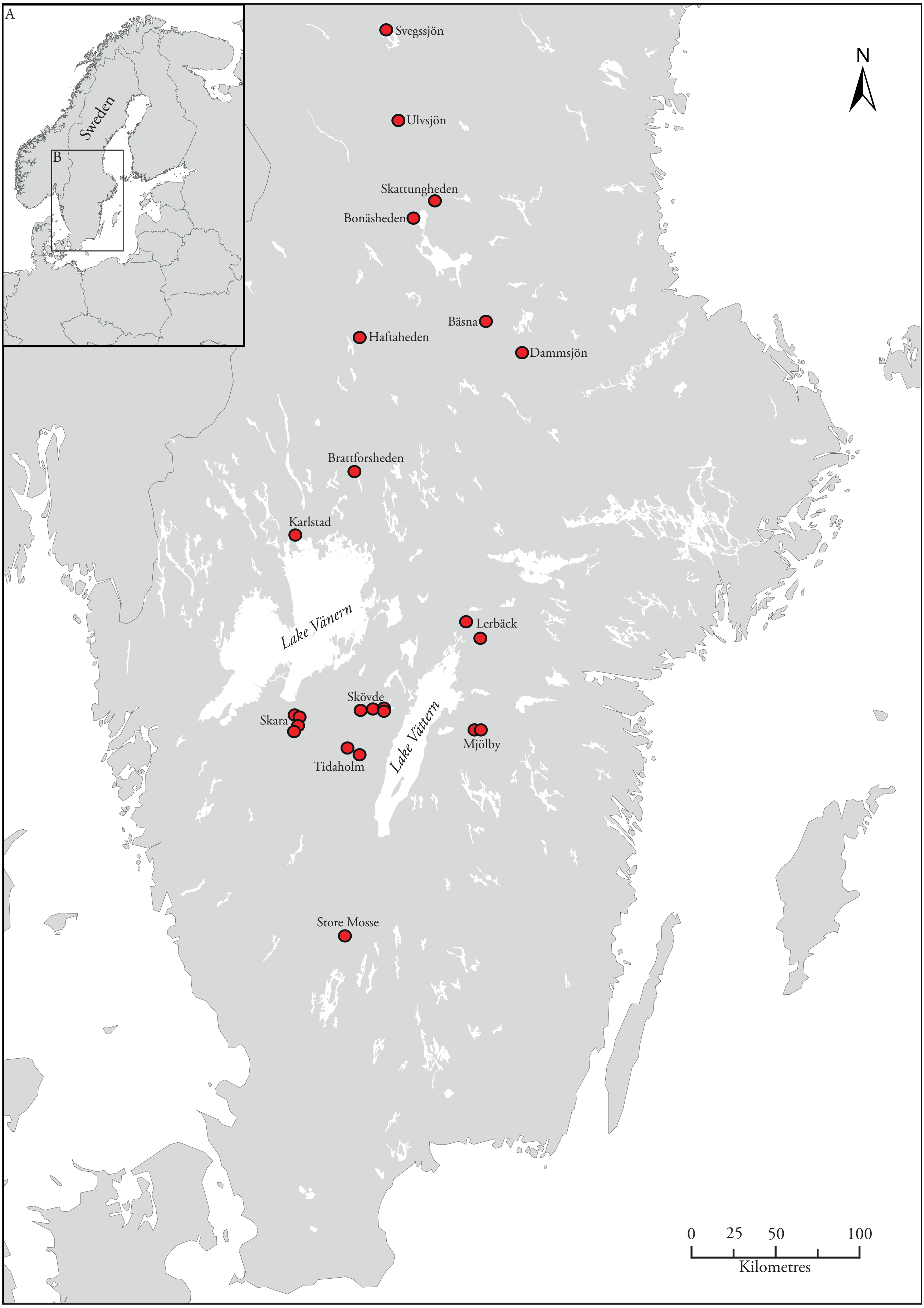

Fig. 3.
A. Map of Scandinavia and the Baltic Sea with surrounding countries. B. Close-up of southern and central Sweden. Investigated dune fields are marked with red dots (© SGU, © EuroGeographics for the administrative boundaries).

stronger than the present day, probably due to a steeper temperature gradient than at present (Seppälä, 2004). The grinding effect of the ice sheets on the underlying sediments and bedrock produced vast amounts of sediment that subsequently were transported by water, forming glaciofluvial, glaciolacustrine and fluvial deposits, in turn forming suitable source material for aeolian sand and loess (cf. Seppälä, 2004). This relationship between glaciofluvial, fluvial, glaciolacustrine and aeolian deposits are noted for large parts of the world, and have been described from many sites in Europe and North America (e.g. Bergqvist, 1981; Bernhardson and Alexanderson, 2017; Halfen *et al.*, 2016; Klemsdal, 1969; Muhs and Holliday, 1995; Seppälä, 1972; Sitzia *et al.*, 2017).

Following the LGM, the Scandinavian Ice Sheet retreated successively and the previously glaciated landscape became either subaerial or inundated by the sea or lakes (Hughes *et al.*, 2016; Stroeven *et al.*, 2016). Based on this it is rather difficult to hypothesise exactly when the aeolian dunes of the Swedish inland formed. Most previous researchers have suggested dune formation in the Swedish inland primarily shortly after local deglaciation (e.g. Högbom, 1923; Hörner, 1927; Nordell, 2007). Still, only taking into consideration the areas of Sweden covered by our investigated dune fields there is an age difference of about 4000 years for local deglaciation (cf. Stroeven *et al.*, 2016), meaning that if all dune fields were formed after local deglaciation we would have a dune archive covering ~4000 years.

With the diminishing ice masses the glacial anticyclone receded in strength to eventually disappear completely (cf. COHMAP Members, 1988; Thorson and Schile, 1995), leading to an atmospheric circulation pattern more similar to the present. Still, the early Holocene was a very unstable period climatically. There were many events when the climate turned colder again, such as the Preboreal climatic oscillation (PBO) and the 8.2 ka event (e.g. Andresen *et al.*, 2006; Björck *et al.*, 1997). This unstable period was likely detrimental to many plant species, delaying the stabilisation of the landscape by vegetation (Seppälä, 2004).

Dune morphology

Most people probably do not reflect on that dunes come not only in different sizes, but also in different shapes, and these features are dependent on the environmental conditions in which the dunes were formed. The abundance of sediment for sand drift, presence or absence of vegetation, local topography, groundwater table variability, strength and mode of the wind can all affect the morphology of dunes (Pye and Tsoar, 1990). The complexity of the dune morphology is highlighted in Fig. 4, where the major dune types according to Pye and Tsoar (1990) are displayed. This figure only show simple dunes; dunes of the same or different types can join together and form more complex patterns, such as compound and complex dunes (McKee, 1979). To make things more complicated the literature is not fully consistent with its terminology; authors use different names for the same or similar dune forms, often based on local names for the dunes, aggravating any comparisons between different regions of the world (McKee, 1979; Pye and Tsoar, 1990).

The most common dune type in formerly glaciated and periglacial areas of the Earth is parabolic dunes (Seppälä, 2004). These dunes are curved in shape (Fig. 5), with their arms pointing towards the dune forming wind direction (i.e. concave towards the dune forming wind), and are partially or fully stabilised by vegetation (Collinson *et al.*, 2006; Pye and Tsoar, 1990; Seppälä, 2004). Parabolic dunes have a gentle windward side and a steeper lee side. In central Sweden transverse dunes, i.e. dune ridges transverse to the dune forming wind direction (Fig. 5), seem to be the most abundant dune type (Bergqvist, 1981; Bernhardson and Alexanderson, 2017, in press; Högbom, 1923; Hörner, 1927). Transverse dunes have a gentle windward side and a steeper lee side (Pye and Tsoar, 1990), with straight or curvi-linear dune crests. Both transverse and parabolic dunes mainly form under unimodal wind directions, with transverse dunes forming when sediment supply is abundant, and little or no vegetation is present (Collinson *et al.*, 2006; Pye and Tsoar, 1990). Parabolic dunes on the other hand are strongly linked to the presence of vegetation (Collinson *et al.*, 2006; Pye and Tsoar, 1990). There exist many other dune types (Fig. 4), but they are less common in Sweden, such as barchan dunes, similar in shape to parabolic dunes, but often unvegetated and convex towards the wind instead of concave (Pye and Tsoar, 1990). Another type is linear/longitudinal dunes that are parallel to the dune building winds, often formed under bimodal wind directions (Pye and Tsoar, 1990), but in some cases are thought to be parabolic dunes were the centre part has been eroded away, leaving only the two trailing arms (Galon, 1959; as cited in Seppälä, 2004). All these different dune types will thus tell us something about the environment in which they were formed.

Study sites and regional setting

The Scandinavian Peninsula has been covered by ice sheets during repeated glaciations (Svendsen *et al.*, 2004). During the LGM the whole of Sweden was covered by the Scandinavian Ice Sheet, which in turn was part of the larger Eurasian Ice Sheet (Hughes *et al.*, 2016; Stroeven *et al.*, 2016; Svendsen *et al.*, 2004). These repeated

Box 2. Aeolian processes

Aeolian processes can be divided into three main categories: *erosion* (removal of material), *transport* and *sedimentation* (deposition of material), with a number of subcategories (Fig. B2; Pye and Tsoar, 1990). Deflation is the direct removal of loose sediment by the wind, while abrasion is the erosion when wind entrained particles collide with a hard surface, such as a boulder; chipping away parts of that boulder (cf. Pye and Tsoar, 1990; Schlyter, 1994). The transportation of sediments can be seen on different scales and the same can be said about sedimentation; movement of individual grains, migration of whole bedforms, and sedimentation of individual grains or stabilisation of whole bedforms (Pye and Tsoar, 1990). These are the processes governing the mobility of individual grains and bedforms.

Looking at a larger scale the ability of the wind to transport sediment is governed by three factors; *sediment supply*, *sediment availability* and *transport capacity* of the wind (Kocurek and Lancaster, 1999). Sediment supply represents the source material of grains of a suitable size for sand drift, while sediment availability represents how exposed these grains are to be entrained by the wind. Transport capacity represents the sediment-carrying capacity of the wind (Kocurek and Lancaster, 1999). To describe it in other words you can say that in order to form aeolian deposits and bedforms you first need a supply of material that the wind can entrain, such as fluvial deposits of an ephemeral river. These deposits must also be available for the wind to entrain; if the fluvial deposits are for example covered by water or vegetation the wind is unlikely to cause sand drift. Lastly, even if there is a supply of sediment available for sand drift the wind needs to be strong enough to be able to transport the sediment for sand drift to take place. All these different factors control sand drift.

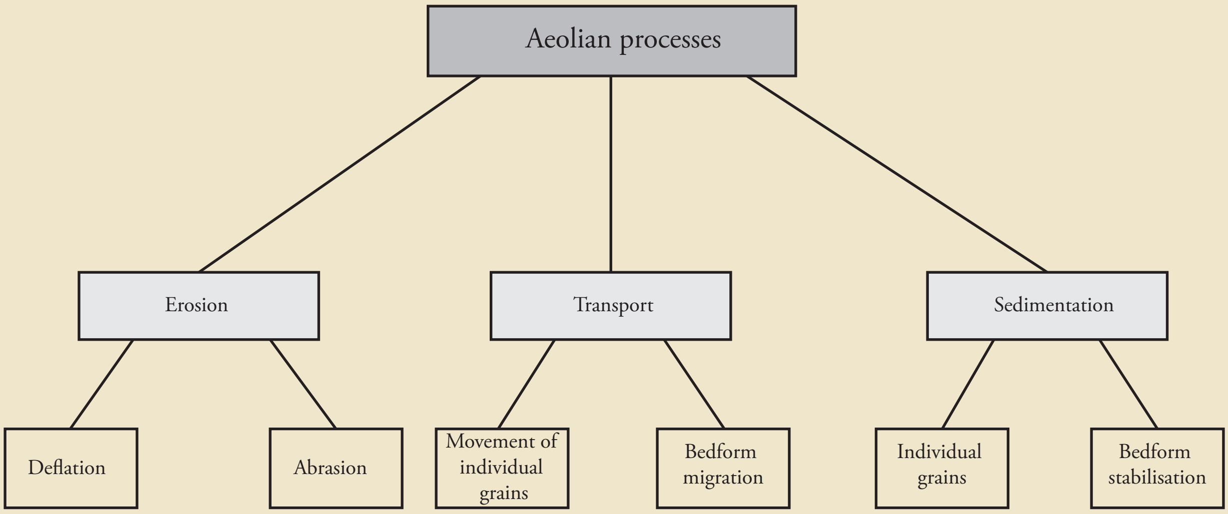

Fig. B2.
The main categories of aeolian processes. Modified from Pye and Tsoar (1990).

glaciation events have left Sweden largely covered by glacial deposits, primarily till (Fredén, 2009). In central Sweden discontinuous soil cover and exposed bedrock is a common sight in the highlands, whereas glaciofluvial, glaciolacustrine, fluvial and other sorted sediments are primarily confined to the lowlands (e.g. Grånäs and Ising, 2008; Hilldén and Mikko, 2013; Ising, 2008). Due to the previously mentioned connection between aeolian and glaciofluvial deposits in Sweden, most of the aeolian deposits and landforms are found in valleys and lowlands, often directly superimposed on their source material (e.g. Bernhardson and Alexanderson, 2017).

Of great importance for the formation of the landscape of Sweden is the highest shoreline, which is the highest elevation the sea, or stage of the Baltic Sea, inundated at deglaciation (Fredén, 2009). The highest shoreline is thus time-transgressive, forming earlier in southern Sweden, and later towards the north. This will affect what type of deposits one would expect to find, since different landforms will form above or below the highest shoreline. Looking specifically at the possibilities for aeolian deposits and sand drift, an area might be completely covered by water after deglaciation. The water must first drain from the area before sand drift may commence (cf. Bergqvist, 1981; Bernhardson and Alexanderson, 2017; Högbom, 1923; Nordell, 2007), something that needs to be taken into consideration when examining dunes that are thought to have formed close after local deglaciation.

The investigated dune fields in central Sweden were chosen to get a good spatial, environmental, chronological and topographical spread in areas. Store Mosse is situated in a part of Sweden that was deglaciated before the Younger Dryas, whereas the Skara, Tidaholm, Skövde and Mjölby dune fields are situated close to the ice sheet terminus

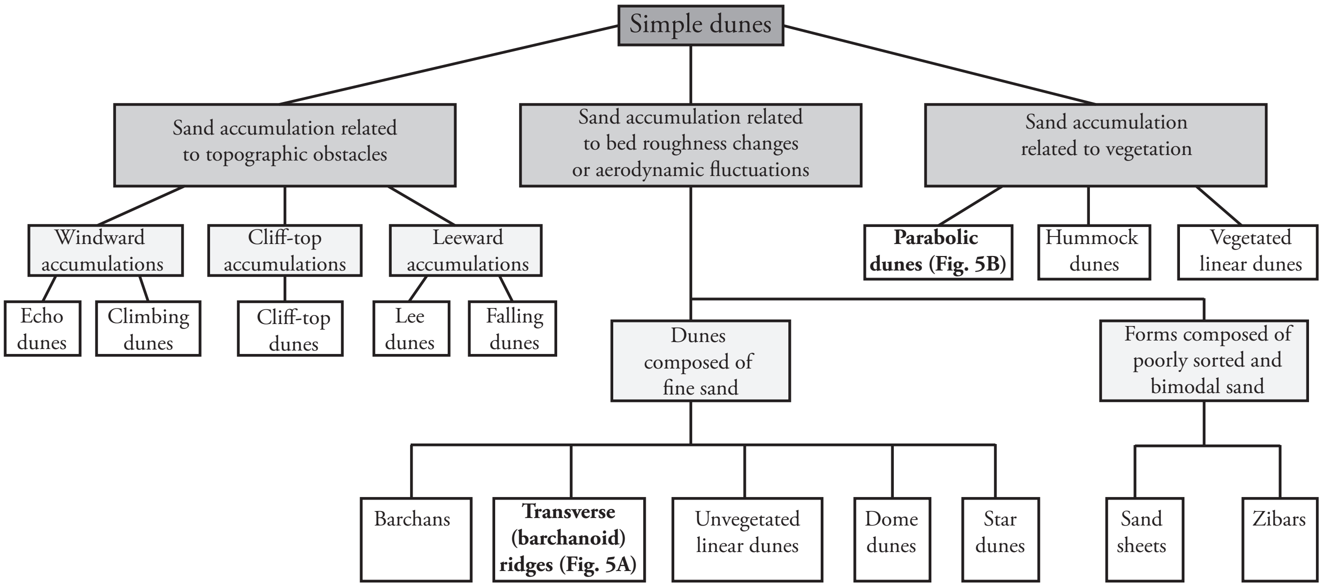

Fig. 4.
Major dune types according to Pye and Tsoar (1990). The most important dune types for this thesis are marked in bold. Modified from Pye and Tsoar (1990).

at Younger Dryas. The Karlstad and Lerbäck dune fields were chosen as suitable sites for the transition between the Swedish central dune zone and the Swedish southern dune zone (Bergqvist, 1981). The Bonäsheden and Brattforsheden dune fields are Sweden's two largest dune fields; they are superimposed on glaciofluvial deltas built up to the level of the highest shoreline. Haftaheden is positioned ~100 m above the highest shoreline, thought to have formed in a glaciolacustrine setting. The Bäsna, Dammsjön and Ulvsjön dune fields are positioned in, or close to, narrow valleys, with Bäsna and Dammsjön having formed around the level of the highest shoreline, whereas Ulvsjön formed above the highest shoreline. Lastly, the dunes at Svegssjön are superimposed on the distal part of a sandur, not confined to a narrow valley.

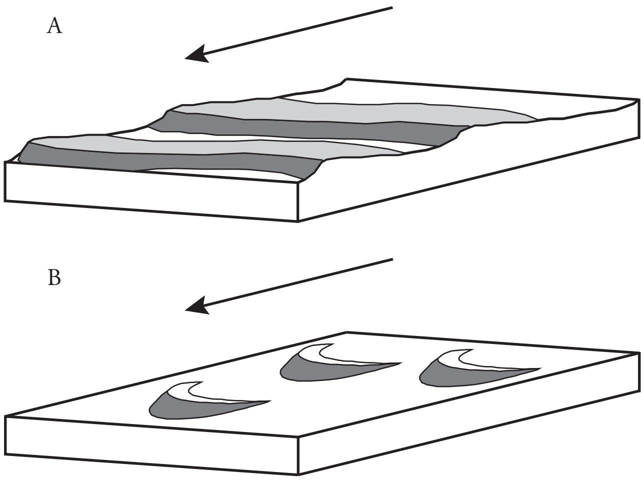

Fig. 5.
The two most common dune types in this study; transverse dunes (A) and parabolic dunes (B). Arrows display the dominant sand transporting wind direction. Modified from Collinson *et al.* (2006).

Material and methods

LiDAR and remote sensing

Most of the remote sensing analyses in this thesis were performed using the LiDAR (light detection and ranging) based new national height model (Ny Nationell Höjdmodell, NNH) of Sweden, which is referenced to the geodetic system SWEREF 99 TM and the height standard RH 2000 (Lantmäteriet, 2015). More precisely this study used the part of the NNH named GSD-Höjddata, grid 2+. Grid 2+ is delivered pre-processed with the changes mentioned below; i.e. vegetation and buildings have been removed, leaving only the underlying topography. The grid 2+ is a terrain model in grid format, with a resolution of 2 m, an average horizontal accuracy of ±0.25 m and an average vertical accuracy of ±0.05 m (Lantmäteriet, 2015). The average point density of LiDAR measurements is 0.5-1 points/m^2 and automated methods were used to classify the laser points into water, bare ground or other. To facilitate the classification of the laser points, the LiDAR is pre-processed using polygon data from Lantmäteriet's Grundläggande Geografiska Data (GGD), containing the extent of water surfaces and buildings.

Other spatial data was used in conjunction with the grid 2+. From the Geological Survey of Sweden (SGU) spatial data concerning Quaternary deposits, bedrock mapping, the highest shoreline and thickness of sediment deposits were used. From Lantmäteriet, besides the LiDAR data, orthophotographs were used.

Box 3. LiDAR

LiDAR is an acronym for Light Detection And Ranging, and works on the same principles as radar, but utilises pulses of laser light instead of microwaves (Lillesand *et al.*, 2008). A number of laser pulses are sent out; when they hit an obstacle they bounce back to their source, often but not necessarily an airplane. The time interval between the emission and reception of these laser pulses are subsequently used to calculate the distance between the airplane and the obstacle (Andersen *et al.*, 2006). One of the advantages of LiDAR is that it is unaffected by conditions like shadows or clouds that would otherwise be a nuisance with more traditional remote sensing tools. Also, the data collected can be directly georeferenced during sampling, making it ideal for use together with geographical information systems (GIS). There are many different types of LiDAR systems, one of the most common ones consists of an airborne laser scanner mounted under an airplane with an IMU (Inertial Measurement Unit) that determines the angular orientation of the laser scanner and an airborne GPS that collects X, Y and Z coordinates (Andersen *et al.*, 2006; Lillesand *et al.*, 2008). With these different systems working together it is possible to reconstruct the 3D vector for each laser pulse, and each reflection can be assigned a 3D coordinate. When LiDAR systems are used for mapping of topographic features pulses are usually sent out in the infrared range (800-1100 nm) of the electromagnetic spectrum (Andersen *et al.*, 2006). Most laser scanners in use can detect many returns per pulse. The differences in returns are due to that the laser hits different objects, some are returned when they reach the top of the forest canopy, others when they hit the undergrowth and some are returned first when they hit the bare earth (see Fig. B3; Andersen *et al.*, 2006). It is later possible to remove unwanted data and just leave the data of interest, like the topography below the forest canopy. The 3D coordinates from the LiDAR mapping are later processed to create a digital elevation model.

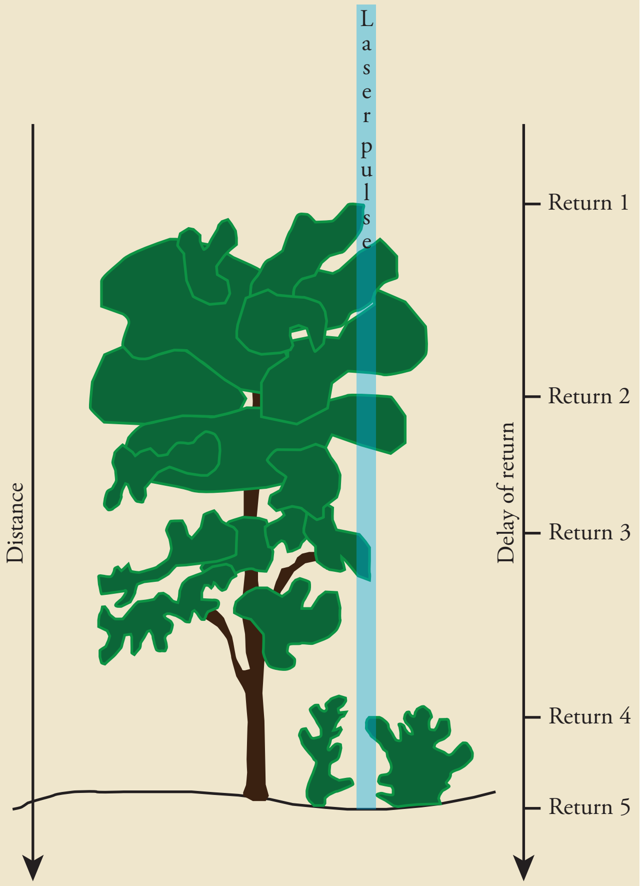

Fig. B3.
Example of a LiDAR mounted on an aeroplane. A signal is returned to the sensor on the aeroplane everytime the laser pulse encounters an obstacle, represented by Return 1-5. Modified from Andersen *et al.* (2006).

Morphological mapping

The digital elevation model (DEM) based on the LiDAR data was processed using the software package ArcGIS (10.0, 10.2.2 and 10.5.1). Among other applications; hillshade models, slope raster images and relief shade models (Fig. 6) were created from the DEM. Hillshade models, where an artificial solar relief creates shaded visualisations of the DEM, will make any landform easier to recognise (cf. Hughes *et al.*, 2010). However, using only one hillshade model that is shaded from a certain azimuth may cause some landforms to be less visible, or even fool the eye to see landforms that are not there. To avoid this phenomenon, termed azimuth-biasing (Smith and Clark, 2005), at least three different hillshade models with different illumination azimuths need to be used (Fig. 7). Hillshade models with an azimuth of 315°, 45° or 0° and a solar elevation of 45° or 90° were mainly used; all having a vertical exaggeration of 5. Slope raster images display the steepness of the terrain in degrees (Fig. 8). This is useful for geomorphological investigations of dunes, as this allow the windward and lee sides of dunes to be identified for a whole dune field (Bernhardson and Alexanderson, 2017). This facilitates classification of dunes into different types (cf. Pye and Tsoar, 1990). The aspect of the dune slopes was calculated in the studies in paper III and IV (Fig. 9). Removing the windward sides of the dunes, thus leaving only the lee side, made it possible to quantitatively infer the net transport direction of the aeolian sand (Bernhardson and Alexanderson, in press).

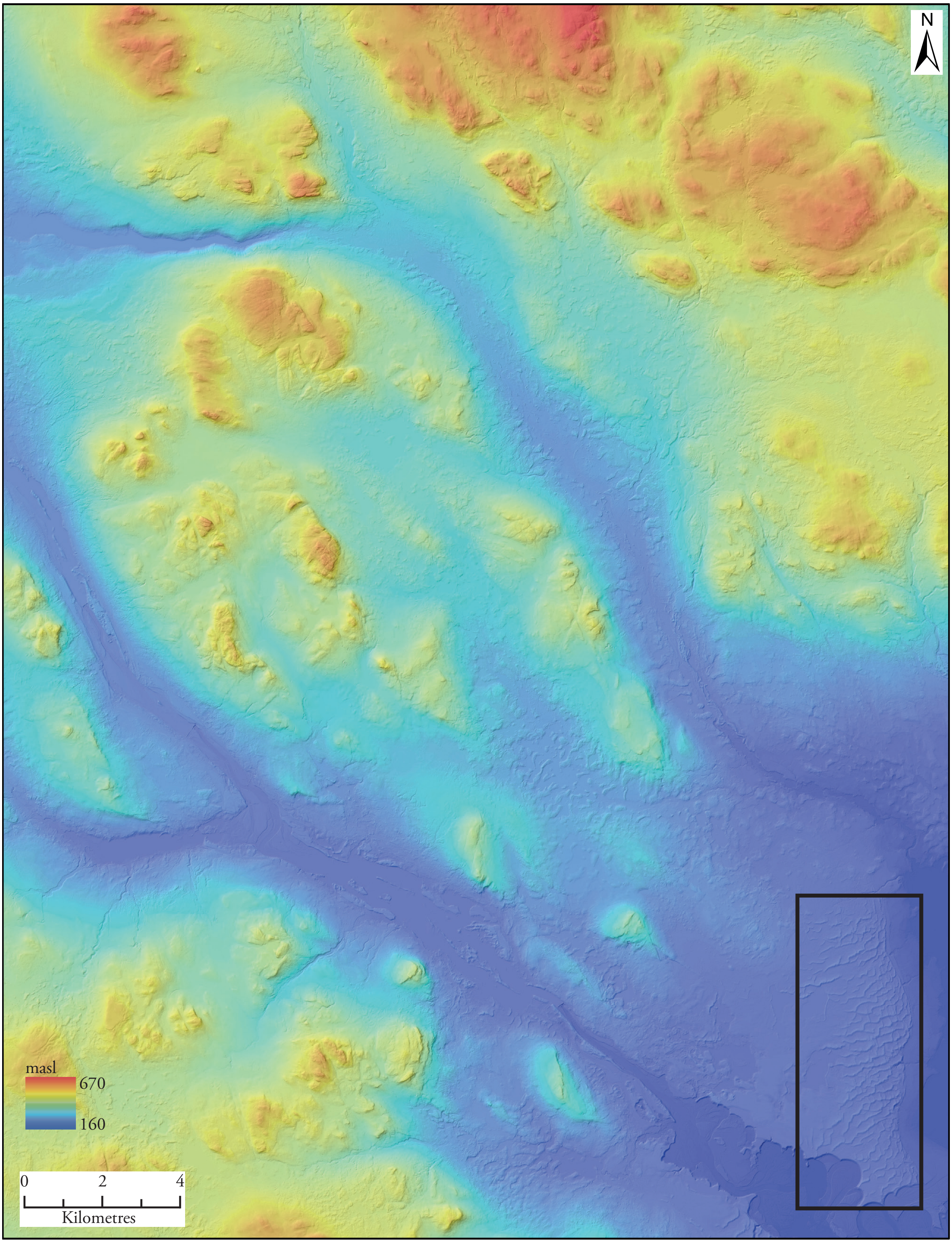

Fig. 6.
Relief shade model with the dune field of Bonäsheden, Dalarna County, marked by the black rectangle (© Lantmäteriet). Modified from Bernhardson and Alexanderson (2017).

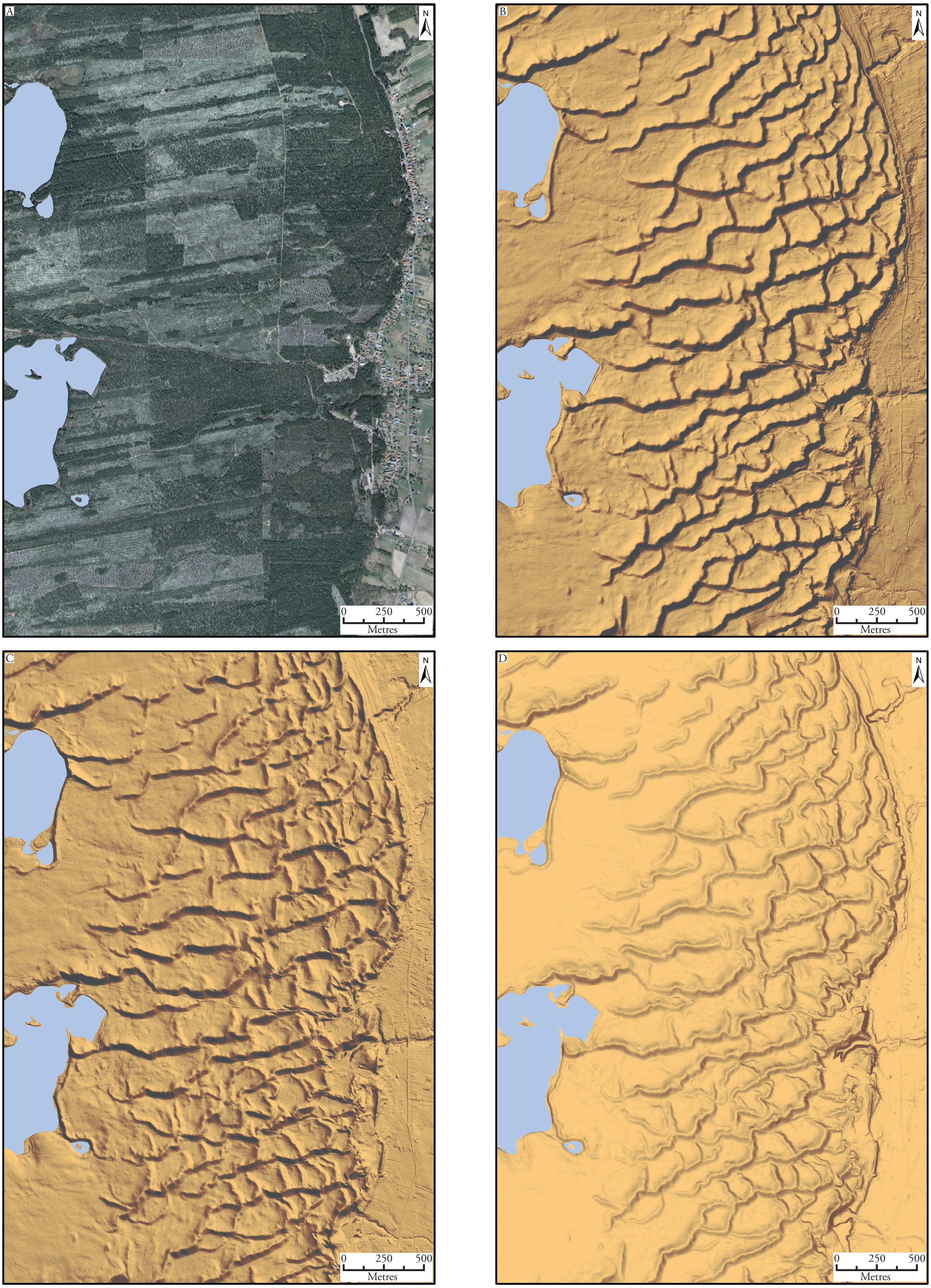

Fig. 7.
An orthophoto (A) and three hillshade models (B-D) over the same part of the Bonäsheden dune field. The figure emphasise two things: 1. The hillshade models display the topography of the dunes in a superior way compared to the orthophoto. 2. Depending on what azimuth and solar elevation are used in a hillshade model the impression of the terrain can differ substantially. Azimuth and solar elevation: B; 315°, 45°. C; 45°, 45°. D: 0°, 90° (© Lantmäteriet).

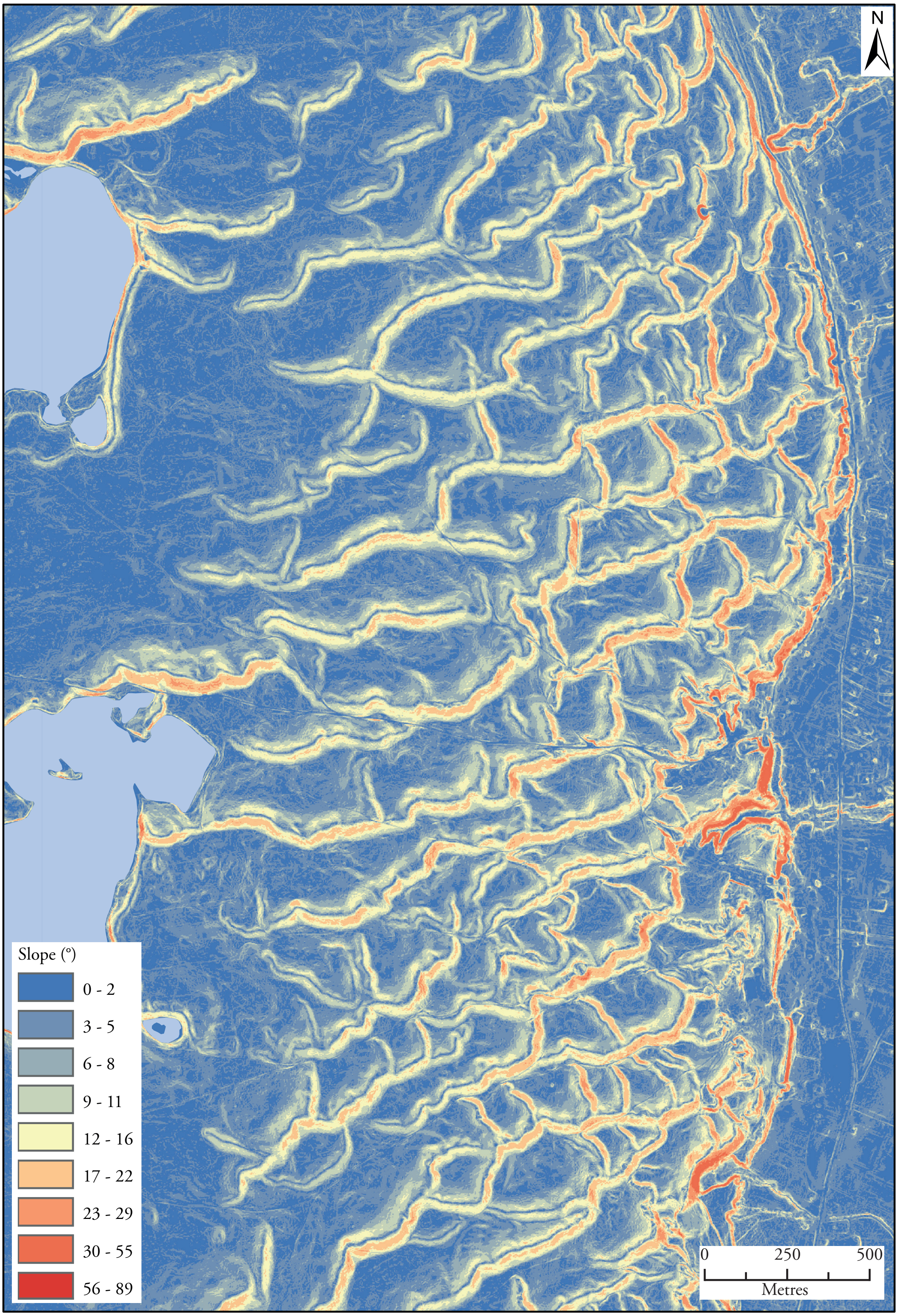

Fig. 8.
Slope raster image over a part of the Bonäsheden dune field. The steepness of the terrain is colour coded, see legend. Notice the difference in slope steepness between windward, blue and yellow, and lee sides, orange and red (© Lantmäteriet).

Literature and map survey

Most research concerning the aeolian inland dunes of Sweden was at its prime during the 1920s, when Högbom (1923) and Hörner (1927) described the two largest dune fields of Sweden, Bonäsheden and Brattforsheden, respectively. Since then the scientific community has been rather disinterested in these landforms, with some noticeable exceptions (e.g. Bergqvist, 1981; Sundborg, 1955). Most of the aeolian deposits of Sweden have been mapped and described by the SGU, often by remote sensing but also from field investigations, and this mapping has been updated progressively (SGU, 2013). Thanks to SGU and previous studies I have a fairly good picture of where these landforms and deposits are situated; however the environmental conditions and their time of formation are still somewhat unclear.

Luminescence dating

Optically stimulated luminescence dating, or OSL dating as it is also known, is an increasingly used dating method in Quaternary sciences. The main advantage of OSL dating is that one can date minerogenic sediments, primarily feldspar and quartz, directly and get an absolute age, something that is not possible with some of the more common dating methods, like radiocarbon dating and palaeomagnetic techniques (Lian and Roberts, 2006), where you have to rely on other materials to retrieve indirect ages or can only get a relative age from your samples. In short, OSL dating depends on radioactivity; radioactive isotopes of thorium (Th), potassium (K) and uranium (U) are often present in the natural environment (Duller, 2008). The energy emission from the radioactive decay can be stored within the crystal structure of some minerals in nature, such as quartz and feldspar. With time, more and more energy is stored in small defects in the crystal structure of the minerals until it at some point becomes saturated or the energy is released, causing a light emission on release, therefore the name luminescence dating. This stored energy (electrons to be more precise) can be released by a number of different ways, but added energy in the form of exposure to a heat or a light source are the most common ones. The magnitude of the light emission from the samples depends on how long the samples have been undisturbed, i.e. the amount of energy stored, and by measuring this magnitude it is possible to determine when they last were exposed to sunlight, usually the time of transportation and deposition (Walker, 2005). The total amount of absorbed energy is measured in the laboratory as equivalent dose (D_e). To calculate the age it is also necessary to know the dose rate, which is the amount of energy absorbed per year from the material surrounding the sediment of interest (Duller, 2008). This varies between sites and sediments. For all of the stored electrons to be released the sediments need to be exposed to sunlight for a sufficient amount of time, if this is not the case only parts of the defects will be emptied before the sediments are reburied (Duller, 2008). If one later tries to date this sample its apparent age will be higher than its actual time of deposition. This is comparable with radiocarbon dating where samples can be contaminated with older material, giving them a false age (cf. Walker, 2005). This state with trapped residual electrons is usually referred to as incomplete bleaching, while samples with no or a small amount of residual electrons are referred to as (well)-bleached (Duller, 2004).

The use of OSL dating for this project appeared promising since aeolian sediments' way of transportation usually allows them to be well-bleached before they are deposited once again, a trait that is not always shared by fluvial or glaciofluvial sediments (Alexanderson and Murray, 2012; Duller, 2004). It should however be mentioned that samples for OSL dating from Sweden have often been problematic since they have poor luminescence sensitivity, leading to poor dose estimates, and in places they overestimate the ages of the deposits, sometimes by as much as 15 times the expected ages (Alexanderson and Murray, 2012). The reason for the age overestimation is thought to be primarily due to incomplete bleaching of the sediments due to their depositional environments. The bedrock of Fennoscandia, including Sweden, is largely dominated by igneous and metamorphic rocks (Lahtinen, 2012). This has some implication for the use of luminescence dating; where sediments derived from sedimentary rocks or long-transported quartz often display higher luminescence sensitivity (and thus yield more accurate ages) than sediments derived directly from igneous rocks, or freshly weathered quartz (Jeong and Choi, 2012; Pietsch *et al.*, 2008). An exception to the poor luminescence sensitivity in Sweden seems to be the Mesoproterozoic Dala sandstone which shows signs of displaying high luminescence sensitivity (Alexanderson and Murray, 2012). The Dala sandstone is present in the bedrock in some of the study areas (Pulvertaft, 1985), and was expected to lead to good age retrievals. Overall these expectations have proved to be correct, since most OSL samples from this area showed good luminescence characteristics (Alexanderson and Bernhardson, 2016; Alexanderson *et al.*, 2016).

The OSL samples were collected in the field by hammering opaque plastic tubes into the sediment, making sure to prevent the material from being exposed to sunlight. Sometimes during the sampling a covered Dutch style hand auger was used to reach sediments deeper in the sand dune (Fig. 10). The water content of the sediment was determined by sampling the same sedimentological units as the OSL samples in small cylinder volumetres, or by using some of the material from the OSL samples. Based on, for example, groundwater levels, sampling depths and

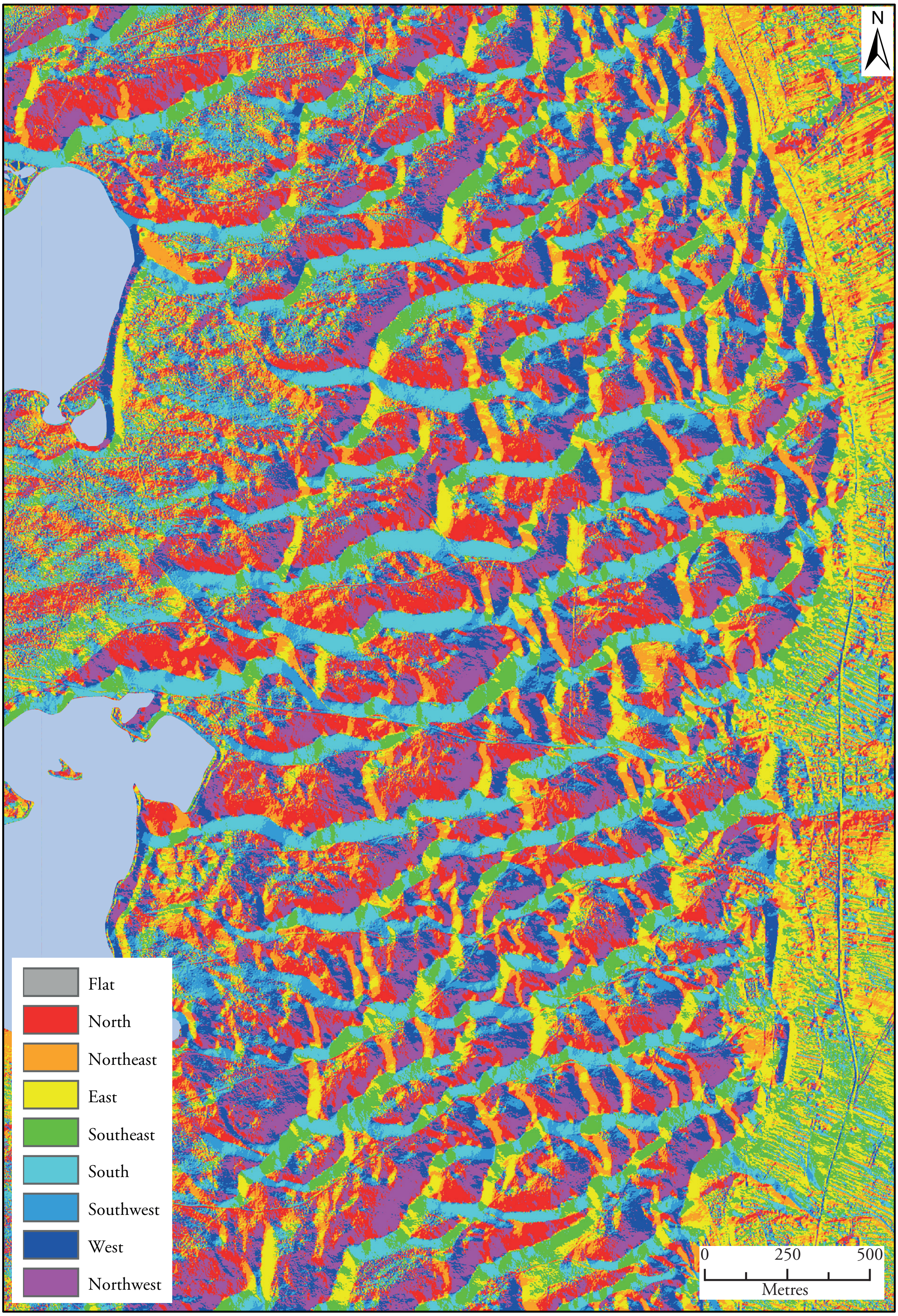

Fig. 9.
Aspect image over a part of the Bonäsheden dune field. The aspect of each cell is colour coded, see legend (© Lantmäteriet).

Fig. 10.
Coring for OSL samples using a Dutch style hand auger. Image courtesy of Johanna Anjar.

topography the average water content is assumed to be closer to the field water content than the saturated water content (Alexanderson and Bernhardson, 2016).

Sedimentology, stratigraphy and geophysics

The project used standard sedimentological and stratigraphical methods, with drawn logs and lithofacies classification, modified from Eyles *et al.* (1983), of encountered sedimentological units. Easily accessible sections, like road cuts and sand quarries (Fig. 1), were prioritised to allow more sections to be investigated during the limited time in the field and to minimise the impact on the landscape. When no road cuts or sand quarries were available the uppermost 1-2 m of the dunes were excavated by hand (Fig. 10).

Of special interest for the project is the orientation of the cross strata in the dunes. By examining the inner structures of the dunes it is possible to judge from where the prevailing wind direction that led to their formation came from (cf. Collinson *et al.*, 2006; Pye and Tsoar, 1990). To further help with this a ground penetrating radar (GPR) was used to get an overview of the inner structures of the dunes at Bonäsheden (paper II) that would be too time consuming, or close to physically impossible, using standard sedimentological investigations.

A closer inspection of the inner structures (Fig. 11) of the aeolian dunes can also reveal information concerning the environment during and after their formation. Certain structures form when the aeolian sand has been intermixed with snow, suggesting transportation and deposition during winter (Seppälä, 2004), structures like ice wedge casts could be signs of former periglacial conditions, certain structures suggest water saturation in the top soil at the time of deposition et cetera (Collinson *et al.*, 2006; Pye and Tsoar, 1990). Some sedimentological structures are thought to be typical for aeolian deposits, one of these are so called pin-stripe lamination, i.e. lamination due to silt and very fine sand getting deposited in wind ripple troughs (Fryberger and Schenk, 1988). Pin-stripe lamination, together with inverse grading in ripples and loosely packed sediment are considered to be characteristic features of aeolian deposits (Collinson *et al.*, 2006; Fryberger and Schenk, 1988; Pye and Tsoar, 1990).

GPR (Fig. 12) is classified as a geophysical method and uses like an ordinary radar electromagnetic radiation, and is usually used to acquire an image of the subsurface (Burger *et al.*, 2006). When the GPR sends high-frequency radio waves into the ground they get reflected back to the GPR. The return signal will change in nature depending on the encountered material's dielectric constant, making it possible to distinguish objects or layer boundaries from each other (Fig. 13). It is possible to alter the frequency used when examining an area with a GPR. There is a trade off with using higher or lower frequencies; a higher frequency yields a better resolution than a lower frequency, but it cannot penetrate as deep into the ground (Burger *et al.*, 2006). Also, the type of material examined can greatly influence how clear the retrieved image will be; for example, finegrained and/or moist soils will often return a blurry image.

Fig. 11.
Road cut through an aeolian dune at Skattungheden, Dalarna County. Image courtesy of Helena Alexanderson.

Summary of papers

Author contribution is detailed in Table 1.

Paper I:

OSL dating and luminescence characteristics of aeolian deposits and their source material in Dalarna, central Sweden. Alexanderson & Bernhardson: 2016, Boreas

This study presents the first detailed absolute chronology for Sweden's largest dune field, Bonäsheden, and the adjacent dune field Skattungheden. Bonäsheden is superimposed on the glaciofluvial Mora delta, which formed at the highest shoreline in central Sweden. In total 12 sites at Bonäsheden and six sites at Skattungheden were investigated and samples collected for luminescence dating. Luminescence ages were primarily retrieved from aeolian dunes, but also coversand deposits, as well as glaciofluvial and paraglacial mass-movement deposits.

The glaciofluvial deposits primarily consist of ripple-laminated fine to medium sand, whereas the paraglacial mass-movement deposits consist of massive, medium sand beds forming a stratified infill, probably in a former delta channel. The dune deposits are often laminated, consisting of fine to medium sand, whereas the coversand deposits primarily consist of massive or vaguely stratified fine to medium sand, superimposing palaeosols. The glaciofluvial deposits are thought to be the source material of the aeolian deposits.

The ages (Fig. 14) show that most of the dunes formed close to the deglaciation during the early Holocene (10.5 ka), in agreement with previous studies, and the dune forming phase lasted until ~9 ka. Our results also suggest four minor events of sand drift, causing deposition of coversand at 4100±200 years, 1569–1412 cal. years BP, 970±60 years and 150±10 years ago. These events were not prominent enough to cause dune migration but only small-scale reactivation over minor parts of the previously formed dune field. The dune field contains quartz grains derived from the Mesoproterozoic Dala sandstone, which previously has been proposed to display properties suitable for OSL dating. The results from this study seem to support this hypothesis, since the luminescence was bright and dominated by the fast signal component, even allowing untreated samples to be analysed successfully.

Paper II:

Early Holocene dune field development in Dalarna, central Sweden: A geomorphological and geophysical case study. Bernhardson & Alexanderson: 2017, Earth Surface Processes and Landforms

Bonäsheden, the largest continuous dune field in Sweden, was investigated using a number of different methods to determine the development of the dune field close after the local deglaciation. A DEM over the dune field was created using LiDAR data. Hillshade models and slope raster images were created for the dune field, and also a triangulated irregular network (TIN) with all the dunes

Fig. 12.
Image of the GPR used during field work. Image courtesy of Helena Alexanderson.

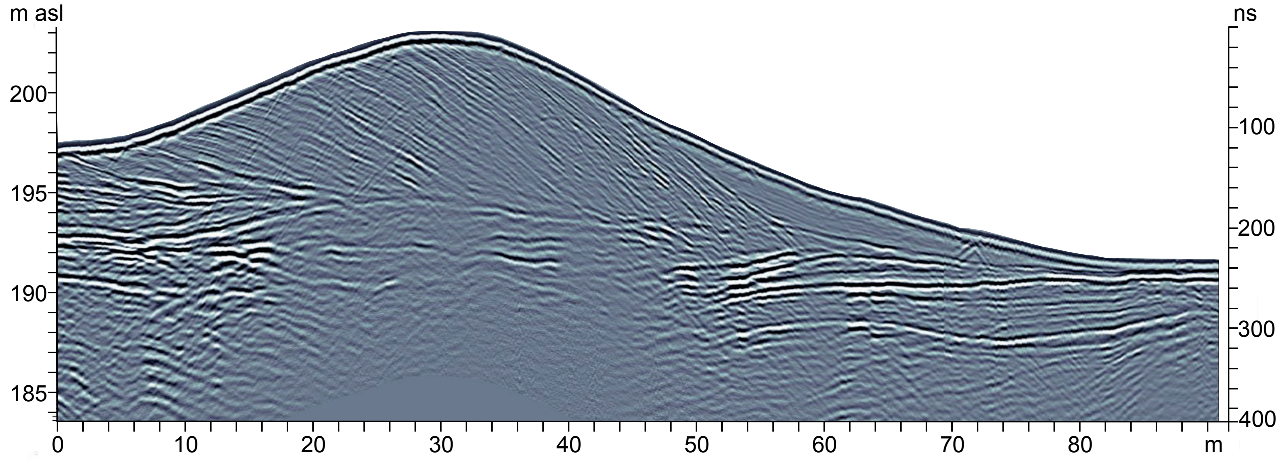

Fig. 13.
GPR profile perpendicular to a dune crest at the Bonäsheden dune field using 200 MHz antennae. Modified from Bernhardson and Alexanderson (2017).

removed from the dune field. By comparing the original DEM (with the dunes) with the TIN (with the dunes removed), an estimation could be made concerning the total volume of sediment in the dunes. The individual dune ridges were mapped from the hillshade models and the slope raster image was used to determine the windward and lee side of the dunes.

Inner structures of some dunes were investigated using standard sedimentological and stratigraphical procedures, and logged at a 1:10 scale. The inner architecture of a number of dunes was examined with GPR. The GPR and sediment mapping are in agreement with the inferred windward and lee side projections indicated in the DEMs, suggesting a net transport direction of sediments transverse to the dune ridges. In total, six different morphological groups were identified at Bonäsheden: (1) Large NE-SW oriented dunes, (2) Large marginal dunes, (3) Small N-S oriented dunes, (4) Small marginal dunes, (5) Parabolic dunes, (6) Coversand.

The majority of the dunes were formed by north-westerly winds close in time to the local deglaciation (~10.5 ka), and their transverse nature suggests formation in a setting with an abundant sediment availability and little or no vegetation present. A younger dune forming phase was noted with dune formation by westerly winds. A schematic model of the dune field evolution is presented: the dune forming winds from NW were amplified by katabatic winds from the retreating Scandinavian Ice Sheet, but after ~10 ka these north-westerly winds were largely replaced by more westerly winds (Fig. 15).

Table 1.
Author contribution to papers. Names are sorted in level of contribution in a descending order. Names in italics are not co-authors, but still offered valuable feedback on the manuscripts. Other people that have contributed to the papers are mentioned in Acknowledgements.

Authors' contribution	Paper I	Paper II	Paper III	Paper IV
Concept and study design	Alexanderson Bernhardson	Bernhardson Alexanderson	Bernhardson	Bernhardson
GIS analyses	Bernhardson	Bernhardson	Bernhardson	Bernhardson
Morphological mapping	Bernhardson	Bernhardson	Bernhardson	Bernhardson
Field work	Alexanderson Bernhardson	Bernhardson Alexanderson	Bernhardson Alexanderson	Bernhardson Alexanderson
GPR interpretation	n/a	Bernhardson Alexanderson	n/a	n/a
Lab work/Luminescence dating	Alexanderson	Alexanderson	Alexanderson	Alexanderson
Data interpretation	Alexanderson Bernhardson	Bernhardson Alexanderson	Bernhardson Alexanderson	Bernhardson Björck Alexanderson Adolphi
Writing	Alexanderson Bernhardson	Bernhardson Alexanderson	Bernhardson Alexanderson	Bernhardson Björck Alexanderson Adolphi
Comments on manuscript	*Möller* *Björck*	*Möller* *Björck*	*Björck*	

Paper III:

Early Holocene NW-W winds reconstructed from small dune fields, central Sweden. Bernhardson & Alexanderson: in press, Boreas

The inland dune research in Sweden has primarily focused on the largest dune fields, despite the higher number of small dune fields scattered across the country. This bias in the scientific literature leaves blind spots in our understanding of sand drift events and the palaeoenvironment. This study focus on five small dune fields in central Sweden, all situated in the same dune region as the two largest dune fields at Bonäsheden and Brattforsheden.

The dune fields in Dalarna County are Haftaheden, Bäsna and Dammsjön, whereas the dune fields in Jämtland County are Ulvsjön and Svegssjön. The dune fields of Bäsna and Dammsjön formed in close connection to the highest shoreline, while the dune fields of Haftaheden, Ulvsjön and Svegssjön formed above the highest shoreline. In common for all of them is that they formed on top of or in close proximity to glaciofluvial deposits. The dune fields were investigated using LiDAR-derived DEMs as well as by field studies. OSL samples were collected during field work to obtain an absolute chronology of dune formation and smaller scale sand drift events. The dune fields mainly host parabolic and transverse dunes, with parabolic dunes being the dominating type at Bäsna, Ulvsjön and Svegssjön, whereas transverse dunes were dominant at Dammsjön and Haftaheden.

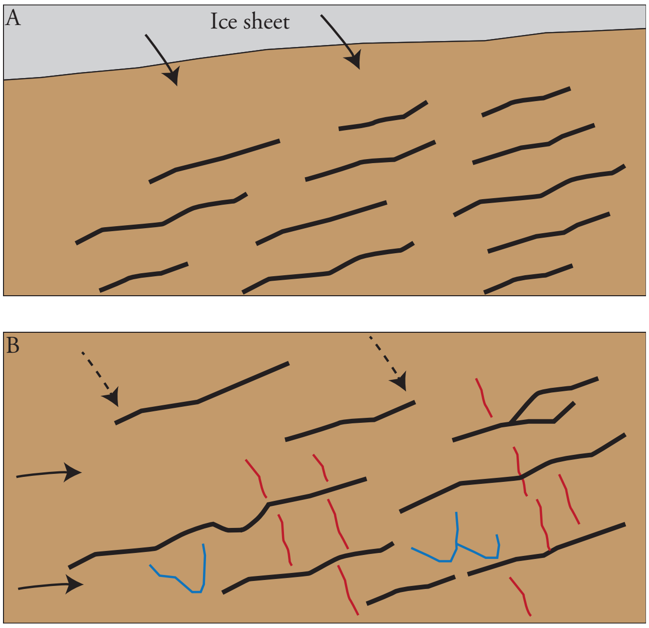

Fig. 15.
Schematic model of the dune formation at Bonäsheden dune field. A. The dune formation was initiated by katabatic winds from the Scandinavian Ice Sheet (~10 ka), creating the large NE-SW oriented dune ridges (black lines). Colonisation by plants started early, rapidly stabilising the dunes. B. Around 9.5-9.0 ka the ice sheet had retreated further away from the area, allowing westerly winds to reach the dune field, forming N-S oriented dune ridges (red lines). Winds from the NW were still present, and during disturbance of the vegetation cover some dunes were reworked into parabolic dunes (blue lines). Figure from paper II (Bernhardson and Alexanderson, 2017).

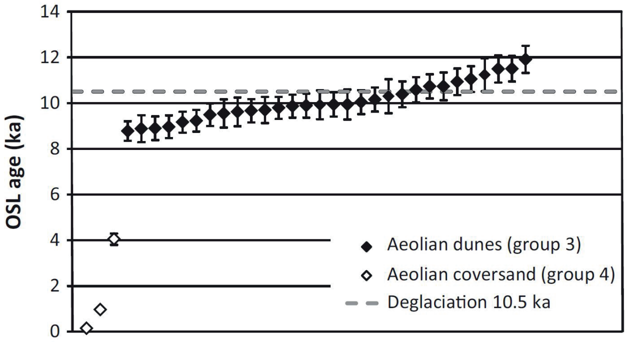

Fig. 14.
OSL ages of aeolian dunes and coversand plotted in order of increasing age. Figure from paper I (Alexanderson and Bernhardson, 2016).

The local topography does not appear to have affected the surface winds that formed the dunes to any noticeable degree, suggesting that the dune orientation might be used as a proxy for regional wind patterns. The OSL ages indicate that most of the dunes formed close after local deglaciation (11-10 ka), with reactivation events around 7.5-6.0 ka and close to the present (Fig. 16).

Paper IV:

Sand drift events and surface winds in south-central Sweden: From the deglaciation to the present. Bernhardson, Alexanderson, Björck & Adolphi: manuscript

In this study we have mapped sand drift events and dune formation over a large part of Sweden and in the process determined when these dunes formed and how the surface winds were directed that led to their formation. This is of interest for the scientific community since up until recent years there has been a general lack of an absolute chronology for aeolian dune formation from Scandinavia.

In this study, the net transport sediment directions for a number of dune fields in Sweden are identified, and the age of these sand drift events and dune formation is determined. Previously published data have been compiled to form a data set of 24 different sites, across a distance of ~540 km from south to north in Sweden. With a few exceptions, winds primarily from the west appear to have been responsible for the dune formation of the investigated dunes, followed by north-westerly winds.

The OSL ages suggest that dune formation took place ~11.5-8.5 ka. Some dune fields formed shortly after local deglaciation, while others formed later. Still, most of the dune fields seem to have had a coeval stabilisation during the early Holocene (Fig. 17). Such stabilisation might be linked to observations in south-central Sweden of very low lake levels around 10.5-9.5 ka BP, which could have prevented dune stabilisation during that time. Another factor that could impede dune stabilisation is the unstable climate during early Holocene. During the mid and late Holocene however, there are very limited events of sand drift, most of them not strong enough to cause dune migration. The most recent events are probably in many cases due to anthropogenic impact removing the shielding vegetation cover.

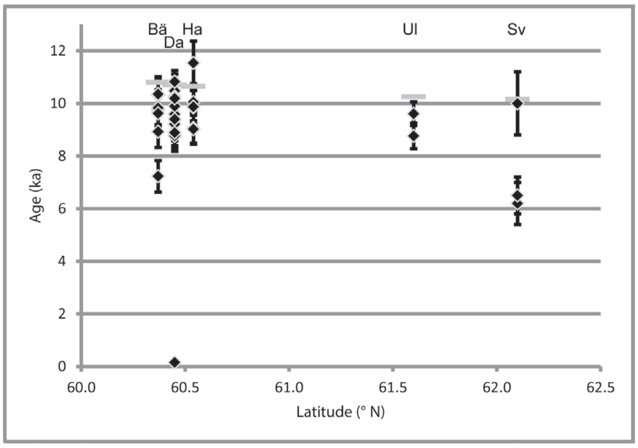

Fig. 16.
OSL ages for each area plotted against latitude. Local deglaciation (Stroeven *et al.*, 2016) is displayed by the grey bars. Bä = Bäsna; Da = Dammsjön; Ha = Haftaheden; Sv = Svegssjön; Ul = Ulvsjön. Figure from paper III (Bernhardson and Alexanderson, in press).

Discussion

Sand drift and dune formation during the early Holocene

The results presented here clearly suggest that the majority of the dunes of central Sweden formed during the early Holocene. One very noticeable thing is that while some of these dunes formed close to local deglaciation, others formed 1000 years, or more, later. In some cases this delay is coupled to an area's relation to sea or lake level history. As an example, most of the Bonäsheden dune field is situated on top of the Mora delta, which formed time-transgressively at gradual shore regression of the Ancylus Lake. Thus, wind activity over the delta continued as new sediments gradually were lifted into subaerial position, which continued for a substantial time after the local deglaciation (~300 years) (Högbom, 1923).

Most of the dune fields are situated in close proximity to, or even superimposed on, glaciofluvial sediment, the source material of most dunes. These glaciofluvial deposits are, however, of varying types: esker ridges, sandurs, glaciofluvial deltas built up to the highest shoreline, glaciofluvial deltas positioned 100 m or more above the highest shoreline (suggesting formation in glaciolacustrine lakes). These local conditions had an effect on when the sediments were susceptible for reworking into aeolian landforms.

It is probably not a coincidence that most of the investigated dune fields appear to have been active at around the same time (10.5-9.5 ka), irrespective of deglaciation age (Alexanderson and Bernhardson, 2016; Alexanderson *et al.*, 2016; Alexanderson and Fabel, 2015), as a period of low lake levels in Sweden (Digerfeldt, 1988; Digerfeldt *et al.*, 2013). Low lake levels and thus low groundwater tables would have had an effect on the mobility of the aeolian deposits in a number of ways. Firstly, the lower lakes levels would make it harder for vegetation to take hold in the landscape, especially if the dunes still were mobile, and the nature of sand itself makes it poor at retaining water (Tsoar and Blumberg, 2002). Secondly, a low groundwater table also means that the interdune area would be dry, which further would promote deflation and sand drift (Pye, 1982). This might partly explain the almost coeval stabilisation of the investigated dune fields in south-central Sweden. Another likely reason why dunes stayed active is that the climate during the early Holocene appears to have been quite unstable (e.g. Andresen *et al.*, 2006; Björck *et al.*, 1997), which would further obstruct colonisation by plants and dune stabilisation.

Pioneer plants that spread over a dune field, and eventually form a total vegetation cover, will reduce the possibility of future sand drift events (Tsoar, 2005). The reason for this is that the vegetation shelters the dunes, therefore making the sediments not available for entrainment by the wind. A forest canopy surrounding a dune field will decrease the surface wind speed, further reducing the wind's erosional ability. Also, plants later in the vegetation succession, such as many tree species, will have a root network that will allow them to reach the groundwater table, even during drier periods. This is probably one of the reasons why the dune fields appears to have been largely inactive during the middle Holocene; and when active it appears to have only been minor events of sand drift, not forming new dunes, but simply reworking the uppermost parts of some dunes or depositing drift sand on top of them (cf. Matthews and Seppälä, 2014).

The few middle Holocene sand drift events have probably had local causes, such as forest fires or changed land use practices (e.g. Bergqvist, 1981). The few very young sand drift events were most probably due to anthropogenic impact; cases of increased sand drift and wind erosion destroying crops after land amalgamation reforms have been described from southern Sweden (Bärring *et al.*, 2003). Such anthropogenic impact is likely the reason why the dunes of the more densely populated southern

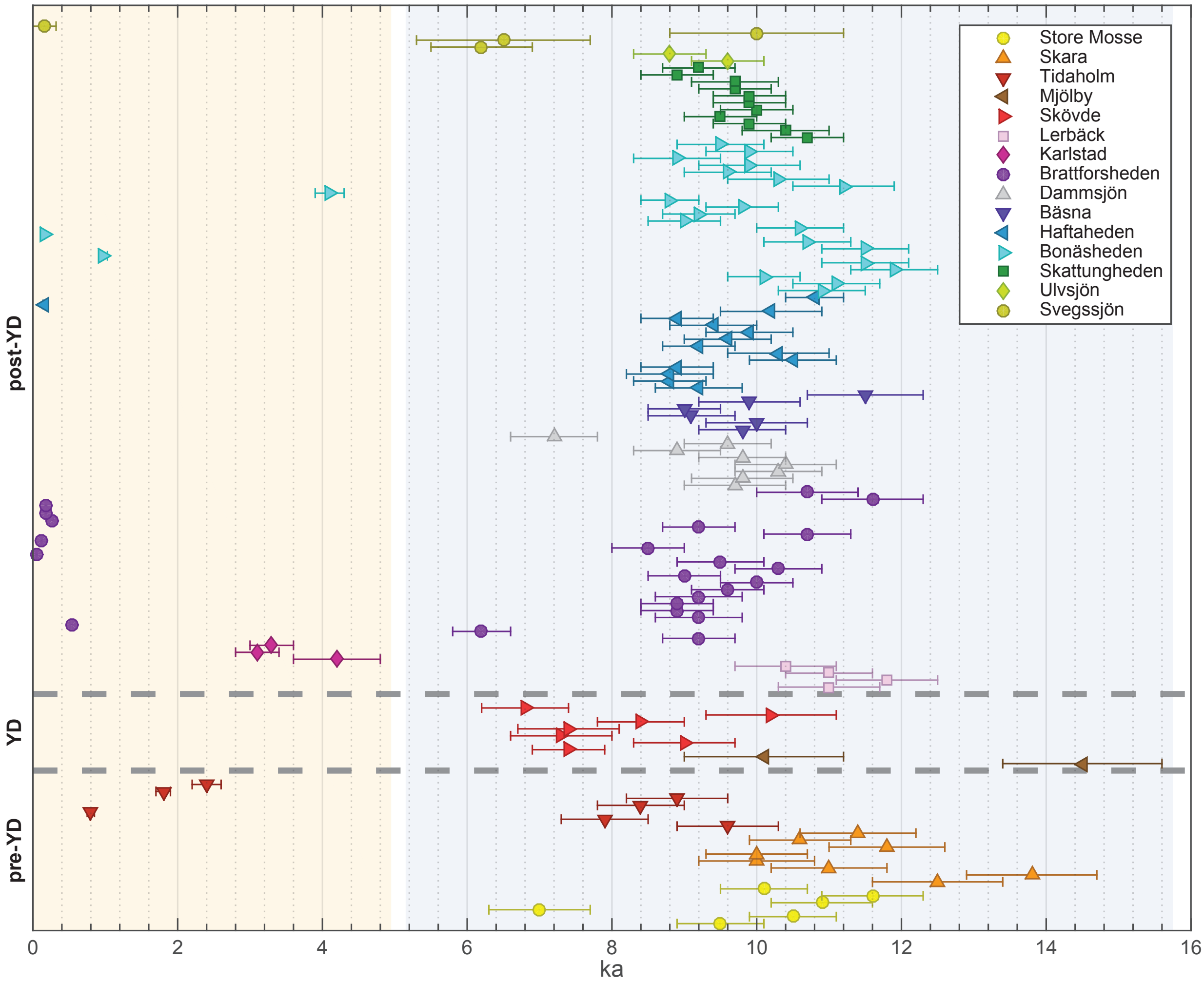

Fig. 17.
OSL ages grouped after their position to the ice sheet margin of the Scandinavian Ice Sheet during Younger Dryas (Stroeven *et al.* 2016). All ages could only be reliable clustered into two groups; one early Holocene group (blue field), and one late Holocene group (beige). Figure from paper IV (Bernhardson *et al.*, to be submitted).

part of Sweden often show signs of more pronounced erosion and reworking (Bergqvist, 1981).

The uncertainty of the absolute chronology

The large uncertainties for most of the luminescence ages cannot be ignored. The period of aeolian activity and dune field formation can be short. As an example, Nordell (2007) proposed that the Bäsna dune field started to form as soon as the area became subaerial due to shore regression and subsequently was stabilised by vegetation, all in less than 100 years. Wolfe and Hugenholtz (2009) showed that barchan dunes from the Canadian prairies got reworked into parabolic dunes within ~70 years, and a similar transformation of barchan and transverse dunes into parabolic dunes within ~50 years has been described from Israel (Tsoar and Blumberg, 2002). OSL ages that have error margins of ±500-700 years on average make it difficult or impossible to differentiate between one long period of active sand drift, or many small ones with stable periods in between. To make things even more complicated, there are some uncertainties in the estimation of the local deglaciation ages of Scandinavia, an error margin of 100-500 years has been suggested for areas deglaciated after the Younger Dryas (Stroeven *et al.*, 2016). This makes it hard to draw any confident conclusions concerning how close to the local deglaciation the different dune fields formed, and implications of this, such as if katabatic winds played an active part in dune formation or not. Still, due to the common lack of organic material in dunes luminescence dating is at the present our most efficient tool in dating aeolian deposits, and the method is improving with time (Lian and Roberts, 2006; Wintle and Adamiec, 2017).

The credibility of the OSL ages can be questioned in some cases. Some luminescence dates gave ages older than the underlying sediments, even within error margins, or gave ages older than that of the local deglaciation. When the uncertainties in local deglaciation ages are taken into consideration most of these ages fall within an acceptable age range, and some samples were problematic to measure (see quality categories in paper IV). These samples are usually found at the lowermost sampled point of the dunes in question, which has two implications: Firstly, the aeolian sediment might have been intermixed with the underlying glaciofluvial material, thus contaminating the samples with too old ages. Secondly, a position low in the terrain means that this part of the dune was more prone to be affected by groundwater table fluctuations, which in turn would have had an effect on the dose rate (cf. Duller, 2008). The few occasions with radiocarbon and luminescence ages retrieved from the same unit mostly showed the ages being in agreement, e.g. Bonäs 3, paper I (Bernhardson and Alexanderson, 2017).

Three zones of aeolian dunes in Sweden

Bergqvist (1981) divided the Swedish aeolian dunes into three regional zones: (i) Northernmost Sweden (Norra Norrbotten), (ii) central and northern Sweden (except northernmost Sweden), and (iii) southern Sweden. Northernmost Sweden is dominated by parabolic dunes, often in conjunction with eskers situated above the highest shoreline (Seppälä, 1972). Many of these dunes display signs of having been reworked (blowouts) and some dunes even show signs of recent erosion and accumulation (Bergqvist, 1981). The majority of the investigated dunes in this thesis belong to the central and northern zone (ii above). Distinguishing for this zone is the abundance of transverse dunes, few signs of reworking, and often close proximity to glaciofluvial deltas. The regional southern zone (iii above), is heavily affected by anthropogenic impact and few 'primary' post-deglaciation dunes are thought to be present (Bergqvist, 1981). Luminescence ages from a coversand sequence in Blentarp, Skåne County, southern Sweden, show five episodes of coversand deposition between ~15-0.15 ka (Shrestha, 2013). The southern dune zone of Sweden has thus been subject to repeated secondary sand drift events, and its use for palaeoenvironmental reconstructions is more complex.

Why the dunes of northernmost Sweden and those of central Sweden are different from each other is probably due to a combination of reasons: Firstly, the northernmost part of Sweden has not been inundated by water to the same extent as south-central Sweden, and is thus mostly positioned above the highest shoreline (SGU, 2015). Most of the dunes described by Seppälä (1972) from northernmost Sweden are situated in close proximity to eskers, while the dunes of central Sweden are usually found in close proximity to, or superimposed on, glaciofluvial deltas, esker beads and sandurs (Bergqvist, 1981; Bernhardson and Alexanderson, 2017, in press; Högbom, 1923; Hörner, 1927). This difference in the nature of the source material probably affects the dune formation; subaerial topset of glaciofluvial deltas would classify as plane source areas according to the definition of Ewing and Kocurek (2010), whereas the eskers in northernmost Sweden most often would qualify as line source areas. Also, the larger abundance of sorted sediments in delta deposits are more favourable for the formation of transverse dunes (cf. Pye and Tsoar, 1990), whereas the dunes in northernmost Sweden (i above), likely started out as barchan dunes that later were reworked into parabolic dunes. Another point worth mentioning is that in a recent study by Matthews and Seppälä (2014), the majority of the investigated aeolian dune fields in northernmost Finland are thought to have formed close to local deglaciation and are of a parabolic type. They identified 16 events of dune reactivation, thought to be initiated by forest fires and thereby removal of the vegetation cover, with prolonged phases of dune stabilisation in between. The same trend has not been seen for central Sweden, where signs of forest fires in the aeolian dune fields are rather scarce. This suggests that sediment availability for sand drift probably has been quite different between the two regions. I have not investigated the dunes of northernmost Sweden, and thus I cannot comment fully on the regional zones of Bergqvist (1981). However, from what I have seen so far for central and southern Sweden, it appears to me that this division of the Swedish inland dunes is adequate, even if reality of course is not as simplistic.

Changes in wind patterns over Scandinavia

The history of the wind pattern changes over Sweden and Scandinavia is still a somewhat uncharted territory. The early theory of north-easterly winds driven by an anticyclone over the Scandinavian Ice Sheet (e.g. Enquist, 1932), is not supported by the inland dune archive. This means that either this anticyclone had decreased in strength to such a degree by the time of the formation of the dunes that it did not affect the surface wind direction to any major degree, or that the interaction between the different wind systems was more complex than previously thought. Markewich *et al.* (2009) faced a similar conundrum for aeolian deposits and wind patterns over North America during the last glaciation and following the deglaciation. The before mentioned simulations by the COHMAP Members (1988) suggested the formation of an anticyclone over the Laurentide Ice Sheet, resulting in a clockwise rotation with northerly to easterly winds affecting the periglacial areas. Instead of the expected northerly winds for the periglacial part of eastern USA, the dunes investigated by Markewich *et al.* (2009), situated outside the LGM limit of the Laurentide Ice Sheet, indicated formation by WNW-NW winds, i.e. as is the similar case for the central Swedish dune fields. The aeolian events in Europe and North America were, however, not coeval; the dunes in eastern North America appear to have formed from 33-15 ka (Markewich *et al.*, 2009), including the time period for the LGM, but not the deglaciation and the Holocene like investigated sites in Sweden. Also, the latitudinal ~20° more southern position of the sites of Markewich *et al.* (2009), compared to ours, make the North American settings even more different. This spatial and temporal differences highlight some important details; Sundborg (1955) hypothesised that the lack of dune formation by north-easterly winds in central Sweden was due to that the Scandinavian Ice Sheet was too small to form a strong anticyclonal wind pattern during the deglaciation of central Sweden. However, the formation of the North American dunes took place within a time period when the Laurentide Ice Sheet still was of a substantial size, at which would be a strong anticyclonal wind pattern. The absence of dunes formed by northerly to easterly winds is seen not just for Scandinavia, but also from sites further to the south in Europe. Here, wind directions inferred from aeolian deposits range from NW to SW, however with an age range from the Weichselian to the present depending on site (as summarised in Koster, 1988).

The differences between the aeolian dune archives and the simulated wind patterns are still not fully resolved. Further investigations into seasonality in wind patterns during the late Weichselian and the Holocene are needed, as well as the impact of, as examples, permafrost and snow cover on sand drift.

Evaluation of state-of-the-art methods

As Seppälä (1972) stated in his study of aeolian dunes from northernmost Sweden; the use of remote sensing, in this case aerial photography, was a method very well suited for studying dune areas in regions with little vegetation. In this thesis the use of LiDAR based DEMs has been extremely useful. As mentioned previously, LiDAR data do not suffer from the masking by vegetation of ground topography. The large present coverage of LiDAR data for the largely forest-covered Scandinavian countries has led to nothing short of a renaissance for geomorphological research; recent papers have highlighted the potential use of this remote sensing technology (e.g. Dowling *et al.*, 2013; Johnson *et al.*, 2015). In paper II the benefits of this new tool is highlighted, where about 100 more individual dune ridges were identified for the Bonäsheden dune field compared to previous remote sensing investigations. The processing of the elevation data using GIS software makes it easy to quantify features such as length, height, area, volume and aspect of the aeolian deposits.

LiDAR based remote sensing has brought many benefits, but words of caution are still advisable. Even though the new DEMs display the landscape in high resolution they still need to be interpreted, and with human interpretations come human errors. I have during discussions with other researchers working with the geomorphology of Scandinavia, using the same grid 2+ terrain model, reached the conclusion that we, as researchers, might initially be biased when we see a hillshade model of a new area for the first time. Where one researcher sees an aeolian dune, another one sees a moraine ridge and a third might see a fragmented esker. These initial impressions of the terrain often quickly disappears after more detailed scrutiny of the LiDAR derived data, but still one needs to be critical of one's own interpretation at all times. This is why complementary investigations in the field, when possible, are advisable.

Conclusions

This thesis sheds light on the use of inland dunes as a palaeoenvironmental archive, even in areas of the world where aeolian deposits are not very abundant and might be easily overlooked. Not only have the studies in the thesis validated or refuted previous research concerning formation of the aeolian dunes in Sweden, especially concerning Bonäsheden (papers I and II), but more importantly presented a detailed morphological and chronological description of a number of smaller dune fields, which often have only been described briefly in the literature. The findings of the studies in this thesis can be summarised as follows:

- Bonäsheden, Sweden's largest continuous dune field, was formed primarily by north-westerly winds during a period of time that was close to local deglaciation of the area (papers I and II). A later dune forming phase occurred around 9 ka, this time by westerly winds. The previous claims by von Post (1934) that the marginal dunes at the eastern part of the dune field were formed by a lake breeze from the east from Ancient Lake Siljan is not supported by our findings. Rather, these dunes appear to have formed by the same winds that formed the majority of the dunes in the dune field.
- There has been a bias in the scientific community to investigate the most prominent dune fields. This has unfortunately led to that many smaller dune fields have received little or no attention, even though they contain the same type of environmental information as larger scale dune fields. This thesis presents palaeoenvironmental data also from small dune fields scattered across south-central Sweden (papers III and IV), offering a better spatial coverage of inferred wind directions and associated time periods for dune formation.

- South-central Sweden is dominated by transverse, and to lesser degree, parabolic dunes. Transverse dunes mainly appear superimposed on glaciofluvial deltas (papers I, II and III).
- The vast majority of the investigated dunes in south-central Sweden were formed by westerly or north-westerly winds (papers III and IV).
- Despite having a difference of as much as 4 ka in local deglaciation age between some dune fields, most of them display ages around 11.5-8.5 ka, which for some sites are just after local deglaciation, while for others the local ice masses were long gone at the time (paper IV). One reason for this might be that the unstable climate during early Holocene aggravated any attempt by plants to stabilise the dune fields. The very low lake levels in southern and south-central Sweden during 10.5-9.5 ka BP would also create an environment favourable for sand drift. The mid-Holocene appears to have been a quite stable period, with only a few minor and local sand drift events. The few late Holocene sand drift events were likely due to anthropogenic impact on the landscape.

Research outlook

The results presented in this thesis provide a synthesis of the complexity between climatic factors and the formation and stabilisation of aeolian dunes in the inland regions of Sweden. Aeolian research is truly a multidisciplinary subject (Fig. B1), and advancements in a number of different disciplines are needed to understand the complex interactions. To mention all these different topics would be worthy of a paper in itself, but some subjects are more directly linked to this thesis than others. Some suggested future research subjects are:

- *Regional high resolution atmospheric circulation models*: High resolution atmospheric circulation models of Scandinavia, covering the period from the deglaciation and throughout the Holocene would be of great interest. Especially models capable of simulating seasonal variations in wind patterns would be interesting; maybe the north-easterly to easterly winds from the assumed anticyclone over the Scandinavian Ice Sheet did indeed affect the areas where the dunes are situated, but only during winter, when the ground was frozen and the sediments probably protected by snow cover. If these models would disagree with our aeolian dune archive, it would be interesting to determine why that is the case.
- *More detailed chronology of sand drift*: Even though the absolute chronology of the inland dunes of Sweden has vastly improved during the last decade or so, there are still many small scale dune fields and coversand areas that have not been investigated yet. Information from these dune fields would help to determine if southern and central Sweden did indeed have a phase of active sand drift that coincided with low lake levels. Also, at some locations only the uppermost 1-2 m of the dunes were sampled. This might cause a bias in the ages since previous events of sand drift further down in the stratigraphy might go unnoticed. From some sites the number of collected OSL samples are just 1-2 samples, making it hard to draw any in-depth conclusions from these sites. Another future endeavour would be to increase the number of OSL ages from aeolian deposits from other parts of northernmost Europe, similar to what has been done for the European sand belt (cf. Tolksdorf and Kaiser, 2012), thus allowing regional and local environmental and climatic fluctuations to be identified.
- *Other palaeoenvironmental archives*: The results presented in this thesis infer sand drift since local deglaciation until ~11.5-8.5 ka. The middle part of the Holocene seems to have been relatively stable, at least with no major disturbances to the vegetation cover draping the dunes. How does this compare with other palaeoenvironmental archives, such as aeolian sand influx in bogs (cf. Björck and Clemmensen, 2004; de Jong *et al.*, 2006) or lakes? This would offer a more continuous archive compared to the dunes, which usually only record one or a few events through time. The use of other, more precise dating methods, such as radiocarbon dating, would also be beneficial to register short term fluctuations in climate, overlooked by the luminescence ages due to their age error bars. This could help to clarify if the early Holocene had one continuous phase of sand drift, or if central Sweden in the early Holocene experienced a number of short episodes of sand drift, with dune stabilisation in between.

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Svensk sammanfattning

I Sveriges centrala inland finns det allt från enstaka sanddyner till stora dynfält som täcker mer än 10 km^2. Dessa dynfält passerar dock oftast obemärkt i landskapet på grund av det oftast markanta vegetationstäcke som fixerar dessa dyner. De är dock värdefulla för att kunna återskapa forna tiders klimat och vindmönster, men tyvärr har förhållandevis lite forskning angående dessa dyner bedrivits under de senaste 90 åren. De primära frågeställningarna i den här avhandlingen har varit varför dessa sanddyner bildades, när de bildades och vad de kan säga oss om tidigare klimatförändringar. Resultaten från detta arbete presenteras i fyra vetenskapliga artiklar.

Sanddyners form och orientering är beroende av den omgivande miljön under deras bildning, såsom mängden tillgänglig sand för vindtransport, grundvattennivå, temperatur, nederbörd, närvaro/frånvaro av vegetation, vindmönster m.m. Genom att identifiera en sanddyns form, och således dess typ, är det möjligt att identifiera de ovan nämnda förhållanden vid dynernas bildning. Om man kan bestämma när dessa dyner bildades kan man återskapa miljön, och i förlängningen klimatet, under en specifik tidsperiod.

I den här avhandlingen presenteras resultaten angående ett antal svenska dyner och dynfälts geomorfologi, geokronologi samt deras paleomiljö. Med hjälp av moderna analysmetoder, såsom LiDAR-baserad (light detection and ranging) fjärranalys och luminiscensdatering, har tidigare forskningsresultat utvärderats samt nya resultat presenterats.

Resultaten visar att dynerna i centrala Sverige huvudsakligen är av en transversell typ, d.v.s. deras dynryggar är orienterade i rät vinkel mot de dynbyggande vindarna, och de bildades i en miljö utan vegetation och med god tillgång till sediment. De primära dynbildande vindarna för dessa transversella dyner verkar ha varit nordvästliga och västliga vindar. De undersökta dynerna längre söderut uppvisar tecken på att ha omarbetats efter deras ursprungliga bildning och är ofta av parabeltyp, d.v.s. bågformade med sina armar orienterade motvinds. Denna dyntyp har beskrivits som starkt länkad till närvaro av vegetation, och kan ofta betraktas som sekundära dynformer. Dessa sydligare parabeldyner tycks, liksom de centrala transversella dynerna, huvudsakligen ha bildats av vindar från nordväst och väst. Dock uppvisar de en större spridning i vindriktningar än de nordligare dynerna.

Luminiscensdateringarna av sediment tagna från dessa dyner visar att de flesta av dynerna bildades och stabiliserades under den tidiga delen av Holocen. Senare fall av sanddrift under övriga delar av Holocen var ovanligt, och hade oftast bara smärre påverkan på dynmorfologin. Det verkar ha varit en primär dynstabiliseringsfas ~10-9 ka, oberoende av dynfältens latitud. Detta innebär att vissa dynfält bildades strax efter den lokala deglaciationen, medan andra bildades betydligt senare. Detta antyder att dynbildning och dynstabilisering i centrala Sverige har styrts av regionala klimatförhållanden. Extremt låga vattennivåer i sjöar i södra och syd-centrala Sverige 10,5–9,5 ka BP, i kombination med ett instabilt klimat under tidiga delen av Holocen fördröjde antagligen dynstabiliseringen av vegetationen. Väl täckta av vegetation var dynerna betydligt mer motståndskraftiga mot vinderosion, även under senare klimatförändringar.