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Alexanderson, Helena; Bernhardson, Martin; Kalińska-Nartiša, Edyta

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Aeolian activity in Sweden: an unexplored environmental archive

HELENA ALEXANDERSON, MARTIN BERNHARDSON & EDYTA KALIŃSKA-NARTIŠA
DEPARTMENT OF GEOLOGY | LUND UNIVERSITY

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Abstract

During the course of this three-year project, we have studied aeolian deposits at 70 sites within sixteen areas in south-central Sweden. Inland dunes have been the focus, but some sites with coversand and coastal dunes have also been investigated. We have mapped dune morphology, mainly by LiDAR-based remote sensing, studied the internal sediment architecture by ground-penetrating radar profiling and in sediment exposures, documented the sedimentology of the deposits with field and laboratory methods as well as determined the age of the deposits with luminescence and radiocarbon dating. In this scientific report to the Geological Survey of Sweden, who funded the project, we present a summary of the project and its results.

The largest and best developed dune fields are found at glacifluvial deposits in Värmland and Dalarna, while in areas south thereof there are mainly scattered dunes or coversand deposits. A range of dune types has been observed, but transverse dunes seem to be dominating and the majority of these are oriented roughly NE-SW. The bulk of the aeolian deposits were formed shortly after the local deglaciation and, once stabilised, do not appear to have been significantly reworked during the Holocene. Most Mid- and Late-Holocene aeolian deposits consist of coversand, apart from in coastal areas where e.g. young foredunes are found.

Our results thus largely confirm the hypothesis of previous investigators but we do add a significant amount of new information. We provide, for the first time for most of our study areas, numerical ages for the aeolian deposits and thus provide the timing and duration of sand-drift events in south-central Sweden. The ages, in combination with detailed geomorphological mapping, allow us to distinguish phases of dune-field development, which are likely due to changes in wind patterns and vegetation cover, and also to correlate Swedish aeolian deposits to regional storminess periods. Based on sedimentological information we are able to reconstruct dominating depositional processes, transport paths and sediment sources. Additional outcomes of the project are e.g. methodological developments (LiDAR mapping, luminescence dating) and pilot studies of potential relevance for applied geology (coastal development).

Populärvetenskaplig sammanfattning

Flygsand har transporterats och avsatts av vind, och den kan bilda landformer som flygsanddyner eller täcksand som draperar marken. I Sverige utgör flygsand bara en liten del av vårt landskap men där den förekommer ger den ofta upphov till speciell natur, som bidrar till både geologisk och biologisk mångfald. Flygsanden kan också berätta en hel del om hur miljön och klimatet var när den avsattes, t.ex. vilka vindriktningar som rådde och förändringar i fuktighet och vegetation som har ägt rum. I det här projektet har vi undersökt främst flygsanddyner, men även andra typer av flygsandavlagringar, på sjuttio olika platser i södra och mellersta Sverige. Vi har beskrivit dynernas form och utseende, undersökt hur de är uppbyggda inuti och hur sanden som de består av ser ut. Dessutom har vi åldersbestämt flygsanden. I den här rapporten till Sveriges Geologiska Undersökning, som finansierat projektet, sammanfattar vi projektet och dess resultat.

Resultaten visar att de flesta flygsanddyner och andra större flygsandavlagringar bildades alldeles efter att inlandsisen smälte bort från Sverige. Den äldsta flygsanden hittar vi därför i Skåne, den är ca 15 200 år gammal, och sedan blir bildningarna successivt yngre norrut och i Dalarna är de äldsta dynerna drygt 10 500 år gamla. Just efter isavsmältningen fanns det gott om sand som nyligen avsatts av isälvarna, endast lite vegetation som band sanden och starka vindar från inlandsisen, allt detta var gynnsamt för dynbildning. Dynernas form visar att de bildades av vindar från nordväst, men det verkar ha skett förändringar i både dynform och -storlek över tid när inlandsisen fortsatte att dra sig tillbaka, vindriktningen ändrades och vegetationen vandrade in. Dynerna var aktiva under ett par tusen år som längst och har därefter varit i stort sett stabila.

De största svenska dynfälten finns i Värmland och Dalarna, dyner finns också i södra Sverige men de är mer spridda och i allmänhet yngre. Under de senaste dryga 7000 åren har det varit ett antal perioder då det avsatts flygsand i dyner i inlandet och vid kusten samt som täcksand. Perioderna verkar vara kopplade till tider med fler och/eller starkare stormar i norra Europa. Under de senaste ca 400 åren har emellertid mänsklig påverkan, t.ex. förändringar i markanvändning, bidragit till att sanddrift skett i vissa områden.

Introduction

Aeolian deposits and palaeoenvironmental information

Aeolian deposits cover large areas in the lowlands of northern Europe and form the so called European sand belt (Koster 1988; Zeeberg 1998). The dunes and coversands of the sand belt are most continuous and also most well studied and dated in its western and central areas, and there regional phases of aeolian activity during the late glacial and the Holocene have been identified (Koster 2005; Tolksdorf & Kaiser 2012; Vandenberghe *et al.* 2013; Zieliński *et al.* 2015). Aeolian deposits further east are patchier and less well studied (Zeeberg 1998; Molodkov & Bitinas 2006; Kalińska-Nartiša *et al.* 2015a; 2015b, 2016). North of the sand belt proper, in Norway, Sweden and Finland, aeolian deposits are mainly found as small inland dune fields or patches of coversand and in some coastal areas (Klemsdal 1969; Seppälä 1972; Bergqvist 1981; Tikkanen & Heikkinen 1995; Kotilainen 2004; Doody 2008), see also Fig. 1. Additionally, wind-transported grains are found in e.g. bogs and lake sediments (Björck & Clemmensen 2004; de Jong *et al.* 2006; Kylander *et al.* 2013; Nielsen *et al.* 2016).

Although the aeolian deposits in Sweden and Norway have been mapped and documented by many geologists/geographers (Fig. 1), studies with a palaeoenvironmental and chronological perspective on aeolian processes or deposits are so far relatively few. In comparison, more work on aeolian deposits has been carried out in Denmark, particularly on coastal dunes (e.g. Kolstrup *et al.* 1990; Clemmensen *et al.* 2001; Clemmensen *et al.* 2009). Also, dunes in northern Finland have been studied in some detail (Tikkanen & Heikkinen 1995; Clarke & Käyhkö 1997; Käyhkö *et al.* 1999; Kotilainen 2004). Recently, there are also a few publications on Swedish and Norwegian dunes (Alexanderson & Fabel 2015; Alexanderson & Henriksen 2015; Nielsen 2016; Nielsen *et al.* 2016), and they indicate the potential of this geological archive. In other parts of the world, studies have shown that much palaeoenvironmental information can be gained from dunes, coversand and loess belts, e.g. complex patterns related to humidity, forest fires, land use, storminess or monsoonal activity have been revealed (Filion 1984; Kozarski 1991; Porter 2001; Kasse 2002; Bateman & Godby 2004; Miao *et al.* 2007; Sorrel *et al.* 2012; Telfer & Hesse 2013). Here we wish to explore the Swedish aeolian record in that respect.

The type of aeolian records that are expected to contain the most comprehensive palaeoenvironmental records in areas such as Sweden are inland dune fields that have been re-activated during the Holocene (cf. Bateman & Godby 2004). They can be used to determine, e.g., palaeowind directions and relative amounts of sand supply and vegetation and will allow us to compare and analyse the same aeolian system under different environmental conditions, one of which likely is impacted by humans. Thin coversands and aeolian silts probably contain only brief records and their main contribution will be to show the extent of aeolian activity in time and space. Coastal dunes also hold potential for palaeoenvironmental reconstruction (e.g. Clemmensen *et al.* 1996), but most Swedish coastal dunes likely reflect mainly recent (historical) phases of sand drift (Lars Clemmensen, pers. comm.), and are controlled by partly other factors (sea level) than the inland dunes, and so records may not be comparable.

**DEFINITIONS –
INLAND DUNES AND COVERSAND**

Inland dunes can be defined in different ways, geographically in terms of their occurrence in continental areas (Pye & Tsoar 2012) or genetically in terms of being formed by inland winds (Högbom 1923). Many Swedish dunes are today found in inland Sweden (Fig. 1), but at their formation they were coastal dunes as they were formed close to the highest shoreline/marine limit. They were not, however, formed by winds from the sea. In this report, we use the term 'inland dune' to refer to dunes presently found in the inland and which were formed by inland winds.

Coversand is here used in its morphological sense, as a thin sheet of wind-blown sand with low-amplitude relief. We do not attach any chronostratigraphic or geographic connotation to it, i.e. not restricting it to the Late Pleistocene of continental Europe (Koster 1982 in Pye & Tsoar 2012).

Aeolian deposits in Sweden

The aeolian record in Sweden is a largely unused palaeoenvironmental resource. Particularly, as few absolute ages of aeolian activity exist, the timing of different sand-drift events is generally not well-determined and causes for sand drift and stabilisation are not well understood. Available age determinations, particularly numerical ones, of Swedish aeolian material have up until recently been few and based on stratigraphy (Lundqvist 1920), relative sea-level change (e.g. Högbom 1923), thermoluminescence dating (Lundqvist & Mejdahl 1987; 1995) or radiocarbon dating of under- or overlying organic material (e.g. Bergqvist &
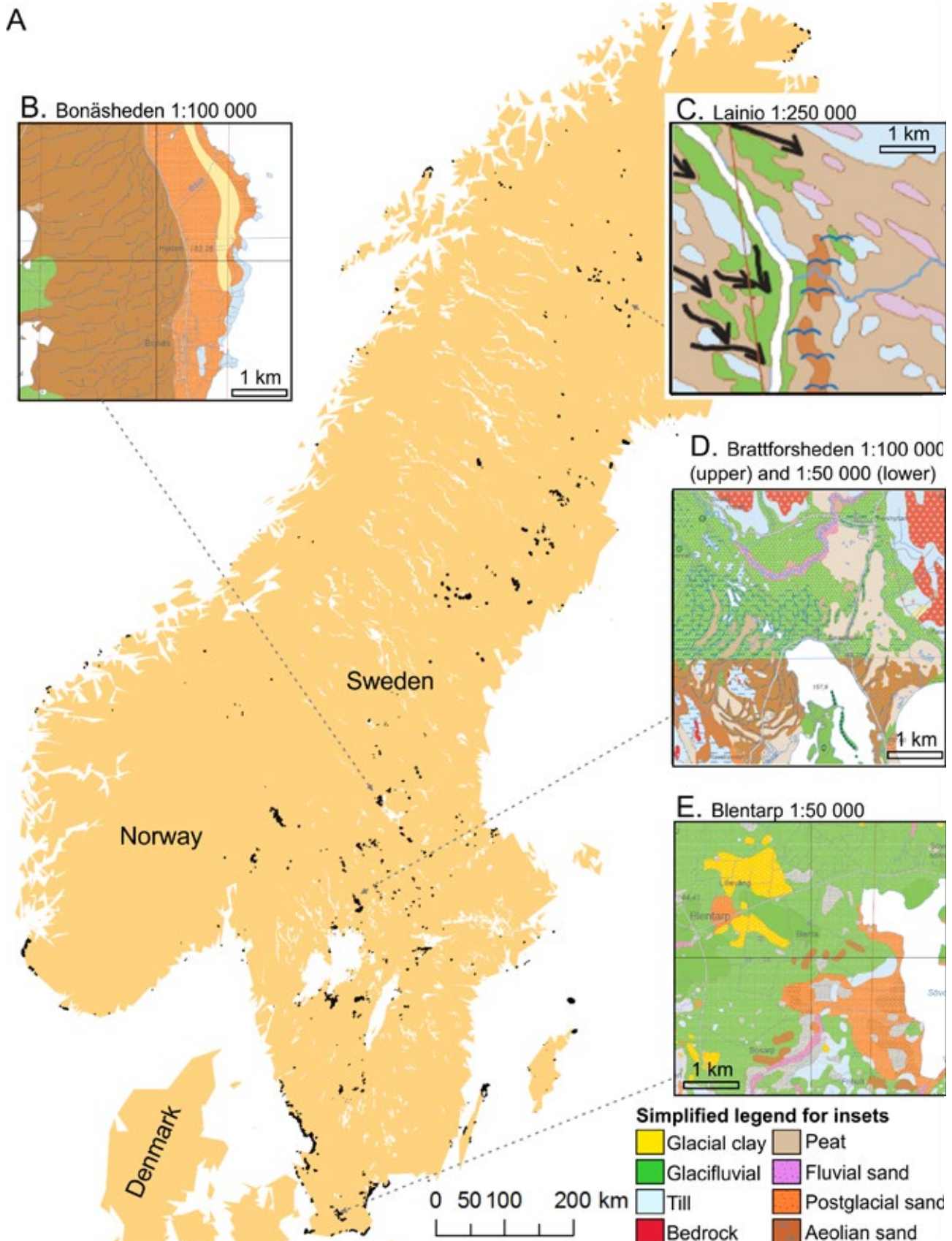
Fig. 1. A. Aeolian deposits in Sweden and Norway as mapped by the Geological Surveys. Original maps are in different scales and hence the black marks on the map may represent individual dunes, groups of dunes, coversand patches or other occurrences of aeolian deposits. The insets B-E show examples of 5x5 km geological maps from four parts of Sweden that were mapped in different scales: B. Bonäsheden, aeolian sand with marked dune ridges mapped in 1:100 000. C. Lainio, aeolian sand with dunes mapped in 1:250 000. D. Brattforsheden, aeolian sand with dunes, in the upper part mapped in 1:100 000, in the lower part in 1:50 000. E. Blentarp, aeolian sand overlying glacifluvial sand, mapped in 1:50 000. Maps show excerpts from SGU's databases Jordarter 1:50k, 100-250k, 750k and 1M, as well as from NGU (2013). Swedish maps © Sveriges geologiska undersökning.

Lindström 1971). Optically stimulated luminescence (OSL) dating, which is a technique well suited for aeolian deposits (Bateman 2008; Lancaster 2008), has only been used in a few recent studies (Davids 2005; Alexanderson & Murray 2012; Alexanderson & Fabel 2015).

The Scandinavian inland dune fields are generally believed to have formed right after deglaciation (Högbom 1913, 1923; Hörner 1927; Seppälä 1972; Bergqvist 1981), mainly because of their association with extensive glacifluvial deposits and their elevation related to relative sea-level change. This is supported by the absolute ages that do exist (Lundqvist & Mejdahl 1987; 1995; Alexanderson & Murray 2012; Alexanderson & Fabel 2015). Thin coversands, which overlie tills and form the base of many of our soils, have been observed in many places (e.g. Hillefors 1969; Svantesson 2001). Occurrences of aeolian silt and loess-like deposits (Hjulström *et al.* 1955; Agrell & Hultman 1971) may derive from the same time period. Coastal dunes are usually younger and closely related to sea-level change (Clemmensen *et al.* 1996; Davids 2005). Some dunes and sand sheets have been reactivated in recent times, which have largely been blamed on human impact or climatic deterioration during the Little Ice Age (Högbom 1923; Klemsdal 1969; Bergqvist 1981; Selsing & Mejdahl 1994; Alexanderson & Murray 2012).

Fig. 2. Number of publications concerning aeolian deposits in Sweden until 2016, based on searches in the Bibliography of Aeolian Research, SGU Georegister and other databases or libraries.

Aim

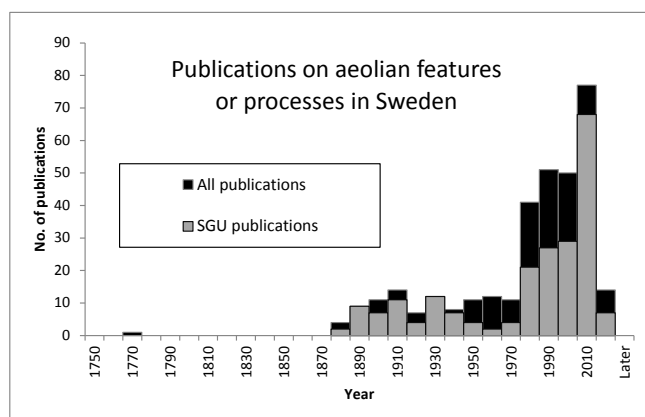The purpose of this project is to study the aeolian record at selected sites in Sweden to determine the timing and magnitude of late glacial and Holocene wind activity and to identify trigger factors in different aeolian settings. With an extensive program for absolute dating, we aim to correlate our data with other regional, hemispheric or global records of environmental change, and explore the interplay between aeolian systems and environmental factors in formerly glaciated areas.

The main research questions that we initially set out to answer are:

1. When did major aeolian events take place in south-central Sweden?

2. Where did aeolian activity occur?

3. How extensive were the events?

4. What were the triggering mechanisms behind any such events?

Wind regimes vary latitudinally and to reduce this variable we have focussed on the Värmland-Dalarna area in Sweden (Fig. 3), which combines nicely with work done together with Norwegian colleagues on sites in Hedmark and Akershus in Norway (Alexanderson & Henriksen 2015; Flatla, unpublished). However, we have also targeted sites along a south-to-north transect, partly to check the timing of aeolian deposition in relation to deglaciation.

The expected outcome of this project was an improved chronology of aeolian activity during the late glacial and Holocene (last ~15 000 years) in the southern half of Sweden. For key sites, palaeowind directions and depositional environments at the time of formation should be reconstructed, and the factors controlling the presence or absence of sand drift identified. To a large extent, we have managed to answer the first three questions and we do now have a much better chronological control of aeolian deposition in south-central Sweden and more information on the depositional environments. The fourth question has yet only been partly addressed. When all data have been analysed, which will be after the deadline for this report, we will be able to better tackle this question and so you will have to look for future publications from us to find the answer.

During the course of the project, we have also acquired results or gained knowledge that is not directly connected to the questions and aims originally stated in the project but nevertheless are of interest and are likely to be paths to future research questions. This includes, for example, methodological advances within luminescence dating, tracing past events of increased storminess and applied use of coastal dune studies for coastal erosion/progradation determination.

Methods

Literature and map survey

Literature databases, including such focussing on Swedish material ('SGU Georegister', http://www.sgu.se/georegister) and on aeolian research (the 'Bibliography of Aeolian Research', http://www.lbk.ars.usda.gov/wewc/biblio/bar.htm), have been surveyed for papers, reports and maps dealing with Swedish aeolian deposits. ArcGIS shapefiles with mapped occurrences of aeolian deposits in Sweden and Norway have been received from the Geological Surveys of Sweden and Norway, respectively (NGU 2013; SGU 2016).

Fieldwork

Fieldwork has been carried out on ten occasions in 2013-2016 at several sites in south-central Sweden (Fig. 3, App. 1). Most fieldwork campaigns were fairly short, from a single day to about a week. Sites were selected based on literature and map studies, as well as geomorphological remote sensing analyses (see below). In the field, sedimentological and geophysical investigations were carried out, including sampling for dating and ground-truthing of remote sensing mapping (see below).

Geomorphological mapping

Hill-shade models, slope raster images and relief shade models were created using the LiDAR based digital elevation model (DEM) Ny Nationell HöjdModell (NNH) from the Swedish national mapping agency and which has a grid size of 2 m (GSD-Höjddata, grid 2+; Lantmäteriet 2015). Despite most of the Swedish inland dune fields being covered by vegetation, the LiDAR based DEM allows the morphological properties of the dune fields to be clearly visualised. More detailed investigations have mainly been conducted for the Bonäsheden dune field and the Haftaheden dune field, Dalarna, making comparisons with the previous mapping by the SGU. The total number of dunes at Bonäsheden was determined together with their length, and an estimation of the total volume of sand in said dunes was also made. All remote sensing analyses were performed using ArcGIS, mostly version 10.2.2.

Selected landforms were ground-truthed in the field and, for some of these, elevation profiles and slopes angles were measured by a handheld GPS and/or a clinometer.

Ground-penetrating radar

A Sensors & Software pulseEKKO PRO ground-pen-
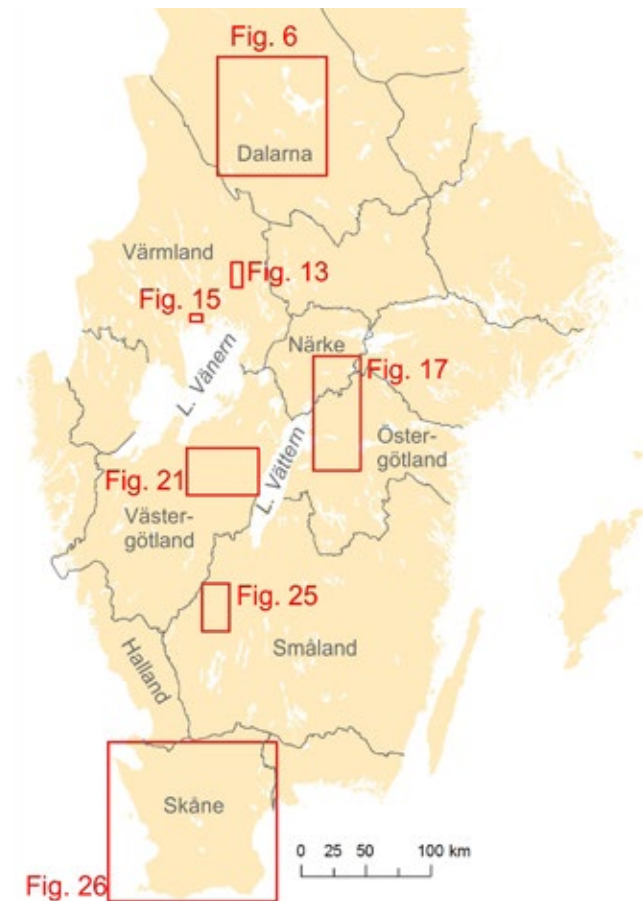
Fig. 3. Our study areas in south-central Sweden and other areas mentioned in the text. The red squares show the location of more detailed area maps.

etrating radar (GPR; Fig. 4) has been used to study the subsurface architecture and internal structures of landforms in Bonäsheden, Skattungheden and Brattforsheden. Profiles were preferably run along and at right angles to the crest of dunes. We mainly used 200 MHz frequency antennas, but at a few sites made supplementary profiles with 500 and 100 MHz, to get better resolution in the uppermost few metres and greater penetration for thick beds, respectively. The GPR data were processed and analysed in the software EKKO_Project 2. The locations of the GPR profiles were logged with a handheld Garmin GPS, and data for topographical correction of the profiles were retrieved from the GSD-Höjddata data, grid 2+ (Lantmäteriet 2015). The reflectors and radar units were described according to nomenclature in Neal (2004). See App. 2 for a list of all sites where GPR profiling was carried out.

Sedimentology

Field work and grain-size analysis

In the field, sediments have been documented by logs, sketches, photos and samples. Where available, we used easily accessible, larger sediment exposures such as sand pits or road cuts. Elsewhere hand-dug pits or

samples from a hand auger were used. Grain size, sedimentary structures, orientations and other relevant features were documented using standard logging techniques.

Limited grain-size analysis (63, 90, 180, 250, 355 µm wet-sieving) has been carried out as part of sample preparation for OSL dating. More detailed determinations of grain size (12 sieves, 63 µm – 22.4 mm) and analyses of grain-size distributions following the logarithmic Folk and Ward (1957) graphical measures have so far been made mainly for sites in Skåne (see App. 2).

Quartz grain analyses

Sediments have been analysed in terms of their textural characterisation, such as single quartz grain shape and character of its surface and microtextures, which serve as potential sources of information on the nature of the sedimentary palaeoenvironment (Mahaney *et al.* 2001; Mahaney 2002; Immonen 2013; Vos *et al.* 2014).

Sandy fractions (0.5-0.8 mm, 0.8-1.0 mm and 1.0-2.0 mm) have been selected, rinsed with distilled water to remove clay particles and observed under a binocular microscope with 30-50x magnification to determine general grain rounding and character of its surface. About 50-150 quartz grains, depending on the type of analysis, were randomly selected from the three grain-size fractions and visually classified. Firstly, the Cailleux (1942) analysis with modification following Mycielska-Dowgiałło and Woronko (1998) was carried out for the 0.5-0.8 mm and 0.8-1.0 mm fraction, which combines three classes of roundness (well- and partially-rounded and non-abraded) with two types of surface (matte and shiny). Secondly, part of the samples were also subjected to the analysis recommended by Velichko and Timireva (1995), where the 1.0-2.0 mm fraction was taken and five groups of roundness combined with four groups of grain surface were distinguished.

Grain microtextures were analysed in two steps with the scanning electron microscope (SEM) at the Department of Geology, Lund University. At first, quartz grains were imaged with ca. 50-100-times magnification to determine the degree of rounding and the general grain relief. Subsequently, magnification at 400-1000-times was used to determine the presence of microtextures. Their classification and terminology followed the proposal of Mahaney (2002) with supplements made by Goudie and Bull (1984) and the semi-quantitative approach recommended by Vos *et al.* (2014).

Fig. 4. Martin Bernhardson and Leif Jakobsen review the results of a GPR profile across the dune at Orsa 3 in Dalarna.

Dating methods

Luminescence dating (OSL)

Luminescence dating, specifically optically stimulated luminescence (OSL) dating, has been the main dating method in this project. Here a generalised and summarised description of the analytical procedure is given; for detailed information on protocol settings and sample characteristics, which vary between sites, please see the scientific publications that deal with chronology (e.g. Alexanderson & Bernhardson in press; Kalińska-Nartiša *et al.* in press).

OSL dating was carried out on sand-sized (180-250 μm) quartz grains and for a few samples also K-feldspar grains (by infrared stimulated luminescence, IRSL), extracted by standard mechanical and chemical techniques from the original sediment taken in opaque plastic tubes (Wintle 1997; Alexanderson & Bernhardson in press). Additional luminescence analyses, including so-called range-finder dating (Roberts *et al.* 2009), were done on untreated sediment, as well as on crushed bedrock samples. Sample preparation as well as most of the OSL measurements were done at the Lund Luminescence Laboratory, Department of Geology, Lund University. A few samples were also measured at the Medical Radiation Physics Department of Clinical Sciences at Lund University/Skåne University Hospital in Malmö.

OSL measurements were conducted on Risø TL/OSL readers model DA-20 (Lund) or model DA-15 (Malmö) with $^{90}Sr/^{90}Y$ beta radiation sources. Large (8 mm) and small (2 mm) aliquots were analysed using single-aliquot regeneration (SAR) protocols (Murray & Wintle 2000; 2003; Banerjee *et al.* 2001), which were adapted to individual samples based on test measurements.

Water content was measured either on separate subsamples in cylinder volumetres (Pusch 1973), taken next to the OSL sample, or on part of the sediment from the OSL sample tube. Both field and saturated water content in weight% was determined, as well as sediment dry bulk density for samples in cylinder volumetres.

Background radiation (dose rate) was determined from sediment from the ends of the OSL sample tubes by high-resolution gamma spectrometry (Murray *et al.* 1987), and by incorporating the cosmic ray contribution (Prescott & Hutton 1994). Part of the sample preparation was done at the Lund Luminescence Laboratory, while final preparation and gamma spectrometry measurements were done at the Nordic Laboratory for Luminescence Dating (NLL), Aarhus University/Risø DTU, Denmark or at the Verein für Kernverfahrenstechnik und Analytik Rossendorf e.V.

(VKTA), Dresden, Germany. Total environmental dose rates were calculated using an Excel spreadsheet (NLL data) and by the DRAC online calculator (VKTA data; Durcan *et al.* 2015).

Note that OSL ages are in years before sampling, not in years BP (Before Present = 1950). To make comparison with C14-ages and historical records easier, young OSL ages have therefore also been recalculated to years AD (Anno Domini).

Radiocarbon dating (C14)

Samples of organic material – terrestrial macrofossils and bulk sediments – have been analysed at the Lund Radiocarbon Dating Laboratory. The radiocarbon ages have been calibrated using the OxCal online software (Bronk Ramsey 2009) and the IntCal13 calibration curve (Reimer *et al.* 2013). It should be noted that the radiocarbon-dated material may either represent surface stability (e.g. macrofossils from palaeosols) or aeolian activity (e.g. charcoal within coversand).

Contributors

Main project group

Prof. Helena Alexanderson has been project leader and as such involved to varying degrees in all parts of the project. She has, however, mainly been working with OSL dating and sedimentology and has been the main investigator of the studies carried out in Västergötland, Östergötland, Närke and Värmland (see p. 18-).

Martin Bernhardson is carrying out his PhD project "Aeolian dunes of central Sweden" as part of this SGU-project. His PhD position is funded by the Faculty of Science, Lund University. Martin leads the investigations in Dalarna (see p. 14-) and focusses on geomorphology, remote sensing and GPR profiling but also contributes to most parts of the project.

Dr Edyta Kalińska-Nartiša has for one year worked as a post-doc connected to this project; her post-doc position ("Marker features of aeolian sediments in Central and Southern Sweden versus environmental factors: New insights from scanning electron microscope (SEM) techniques") was funded by the Swedish Institute's Visby programme. She has also worked as laboratory assistant in the Lund Luminescence Laboratory for three months. Edyta led the investigations in eastern Skåne (see p. 28-) and contributed with expertise in OSL dating and sedimentology, particularly quartz grain analyses.

Sara Florén has worked as laboratory assistant in the Lund Luminescence Laboratory mainly with sample preparation. She has also participated in field work

in Småland and Dalarna.

Students

Rajendra Shrestha carried out the chronological and stratigraphical work done on coversands in Blentarp, Skåne within his master thesis (Shrestha 2013). *Björn Olsenius* reviewed literature and historical maps for information on sand drift on the Kristianstad plain in his bachelor thesis (Olsenius 2014). *Marijana Stevic* analysed sand grains from dunes in Vittskövle and Brattforsheden in her bachelor thesis (Stevic 2015). *Mark Björnfors* worked with coastal dunes in the Ängelholm area in his bachelor thesis (Björnfors 2016). *Mohammed El Ali* studied GPR profiles from Bonäsheden in his bachelor thesis (El Ali in prep.) and has participated in field work in Haftaheden.

Fig. 5. The main project group at a section in one of the dunes at Store Mosse, Småland. From left to right: Martin Bernhardson, Sara Florén, Edyta Kalińska-Nartiša and Helena Alexanderson.

Results

Overview

During the three years of the project (July 2013 - June 2016), 70 sites from Åhus in the south to Skattungheden in the north have been visited (Fig. 3, App. 2). We have gathered sedimentological and stratigraphical data from these sites and mapped their surroundings. In total, 152 samples for OSL dating and 9 samples for radiocarbon dating have been taken. GPR profiling was carried out at 20 sites (App. 2). In addition, we have applied new techniques (e.g. quartz microstructures) to previously sampled material from sites at Brattforsheden and Starmoen.

Below, the work done in the different areas is briefly presented, in order from north to south. As all data are not yet published or fully analysed, much of the results here are summarised or preliminary only. For details, please see final publications (so far Alexanderson & Bernhardson in press; Kalińska-Nartiša *et al.* in press).

Dalarna

Three dune fields have been investigated in Dalarna: Bonäsheden, Skattungheden and Haftaheden (Fig. 6). Bonäsheden is situated just west of Lake Orsasjön, Dalarna, and covers an area of ~15.5 km^2 (Bernhardson & Alexanderson submitted), see Fig. 6. It is the largest continuous dune field in Sweden and has been of interest for Swedish Quaternary geologists for over a century (Högbom 1913, 1923; Bergqvist 1981; this study). Bonäsheden and the adjacent dune field of Hemusheden are superimposed on a glacifluvial delta formed around the highest shoreline; the Mora delta (Bergqvist 1981). Previous authors have, mainly based on geomorphology, interpreted

Fig. 6. Investigated dune fields in Dalarna marked by red dots. The background map shows lakes and railroads. © Lantmäteriet (i2012/927)

the dunes of Bonäsheden as transverse and that they were formed by north-westerly winds, however some studies provide only little evidence to support their interpretations. Evidence from our field investigations, geophysical, geomorphological and sedimentological data, do indeed suggest that most of the dunes are of a transverse type (Bernhardson & Alexanderson submitted). They have clear windward- and lee sides, not always obvious in hill-shade models (Fig. 7) but clear in the field and in slope raster images (Fig. 8). However, other dune types and dunes with a different orientation have also been identified (Bernhardson & Alexanderson submitted).

Comparison between previous investigations by the SGU, using more traditional remote sensing and mapping methods, show that despite using the same map scale, the LiDAR based data used in our project display a higher level of detail concerning the number of dunes and their geomorphology.

Skattungheden is situated north-east of Orsa and Lake Orsasjön (Figs. 6, 9). The dune field shows many similarities with Bonäsheden and Hemusheden, not surprising since the dune field is just located ~13 km from Bonäsheden. Geochronological investigations suggest that both dune fields – Bonäsheden and Skattungheden – formed close following the deglaciation, and later aeolian activity has been limited to patchy coversand deposition in the area (Alexanderson & Bernhardson in press; Bernhardson & Alexanderson submitted).

Haftaheden is situated SSE of Yttermalung and SW of Äppelbo, Dalarna, ca 75 km south-west of Bonäsheden (Fig. 6). It differs from Bonäsheden and Brattforsheden in that it is located well above the highest shoreline of the area, thus having formed in a different setting (Bergqvist 1981). Most of the dunes have a dune ridge orientation trending N-S to NE-SW. Just as in Bonäsheden a number of different remote sensing and field investigation methods were used (cf. Bernhardson & Alexanderson submitted, Bernhardson, in prep.). Preliminary data indicate that the majority of the dunes at Haftaheden are of a transverse type and thus seem to have formed by westerly to north-westerly winds. Preliminary OSL ages suggest that the dune field was active for a few thousand years shortly after the deglaciation, but once stabilised was inactive for most of the Holocene (Bernhardson, in prep.).

GPR profiles across selected dunes in Dalarna reveal that the bulk of the dunes consists of foresets dipping toward the steeper part of the dune. i.e. towards the lee side (Fig. 10). No or few bounding surfaces are observed within the foresets, which are long and with a dip generally less than the angle of repose. Trough-
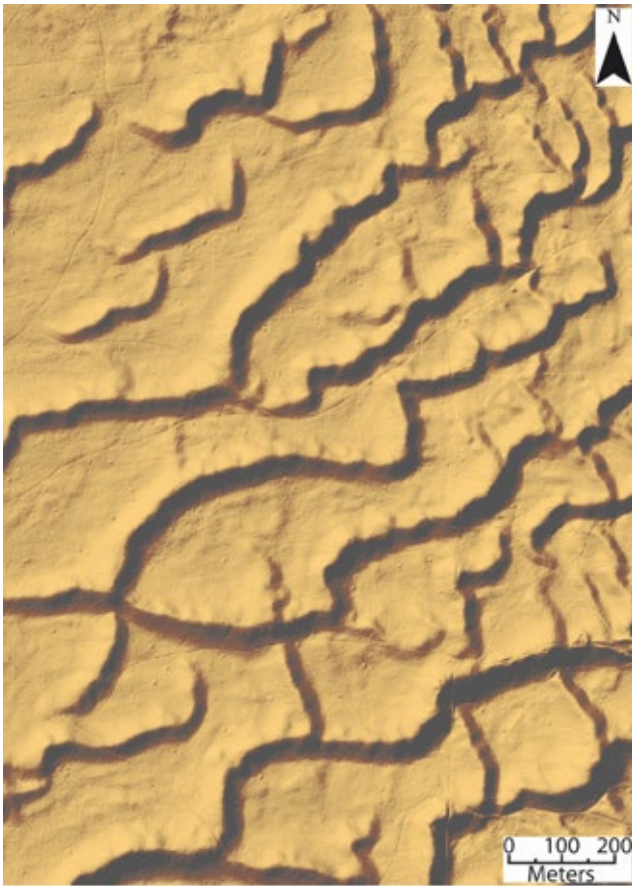
Fig. 7. Hill-shade model of part of Bonäsheden with an azimuth of 315°, an illumination angle of 45° and a vertical exaggeration of 5 (© Lantmäteriet, i2012/927).
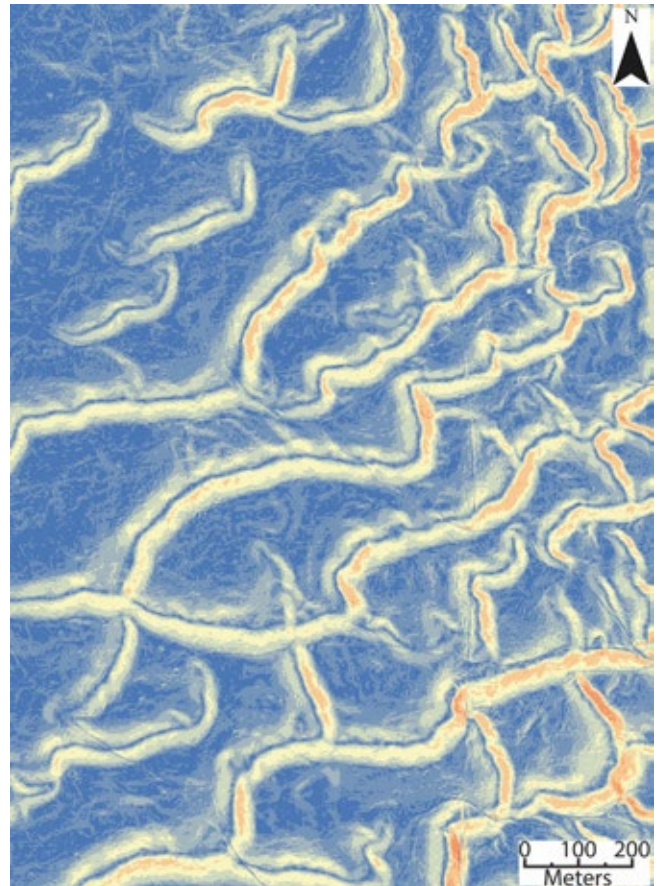
Fig. 8. Slope raster image of part of Bonäsheden (© Lantmäteriet, i2012/927). Blue shows a low slope angle, while yellow and red show a steeper slope angle. The steeper lee sides facing SE are clearly distinguished in this type of image.

Fig. 9. Road cut through one of the dunes in Skattungheden. The gently sloping windward side of the dune is towards the left in the photo.

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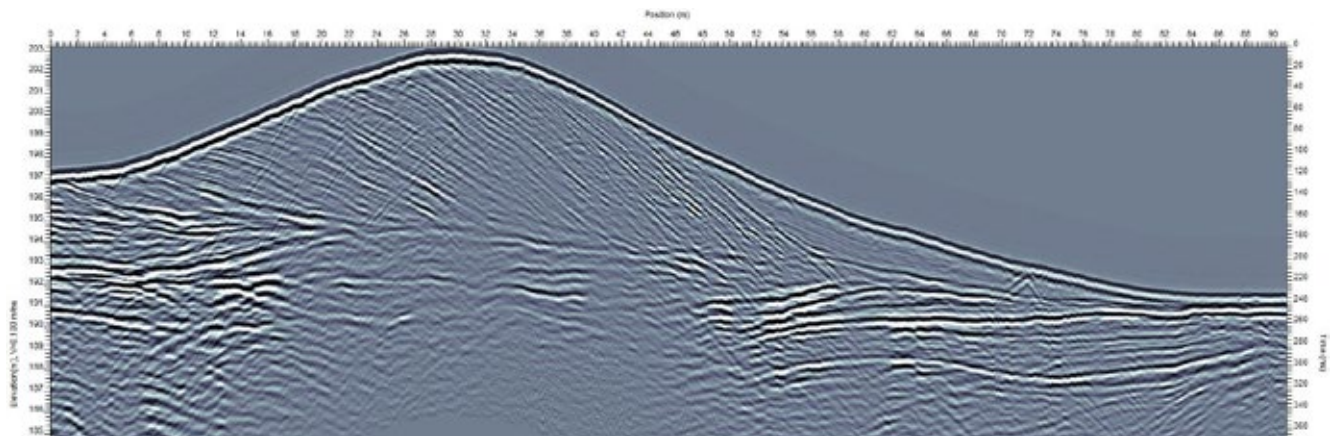
Fig. 10. Example of 200 MHz GPR profile from a dune at Bonäsheden. The profile is oriented NNW-SSE and perpendicular to the dune ridge orientation with the cross-stratification clearly visible. The strong more or less horisontal reflectors at ~192-193 m elevation are interpreted as the boundary to the underlying glacifluvial sediments. No major bounding surfaces or unconformities are visible within the dune, but an apparently massive or weakly stratified unit is identified at the toe of the dune (right in picture).

shaped units overlying the foresets or wedge-shaped units at the toe of lee-sides are seen in some dunes (Fig. 10).

Sedimentologically, the dune sands of Bonäsheden and Skattungheden are dominated by distinctly laminated fine-medium sand (Fig. 11A), much of which is interpreted as pinstripe lamination, a result of wind-ripple migration (Fryberger & Schenk 1988). In many places, laminations were synsedimentary disturbed by some kind of digging organism (Fig. 11B). Massive and graded beds were also observed (e.g. Fig. 12B-E). Coversand, which was found in a few places, is dominated by massive sand and influenced by soil formation.

In the paraglacial and glacifluvial sands at Bonäsheden (e.g. Fig. 12), non-abraded ('fresh') and weathered quartz grains dominate. Such grains are also present in dune sediments, however with an increas-

Fig. 11. A, left. Distinctly laminated fine-medium sand dominates in the Bonäsheden and Skattungheden dunes, here from the site Orsa 3. B, right. Synsedimentary bioturbation has disrupted the laminations in many places. Example here from Orsa 3.
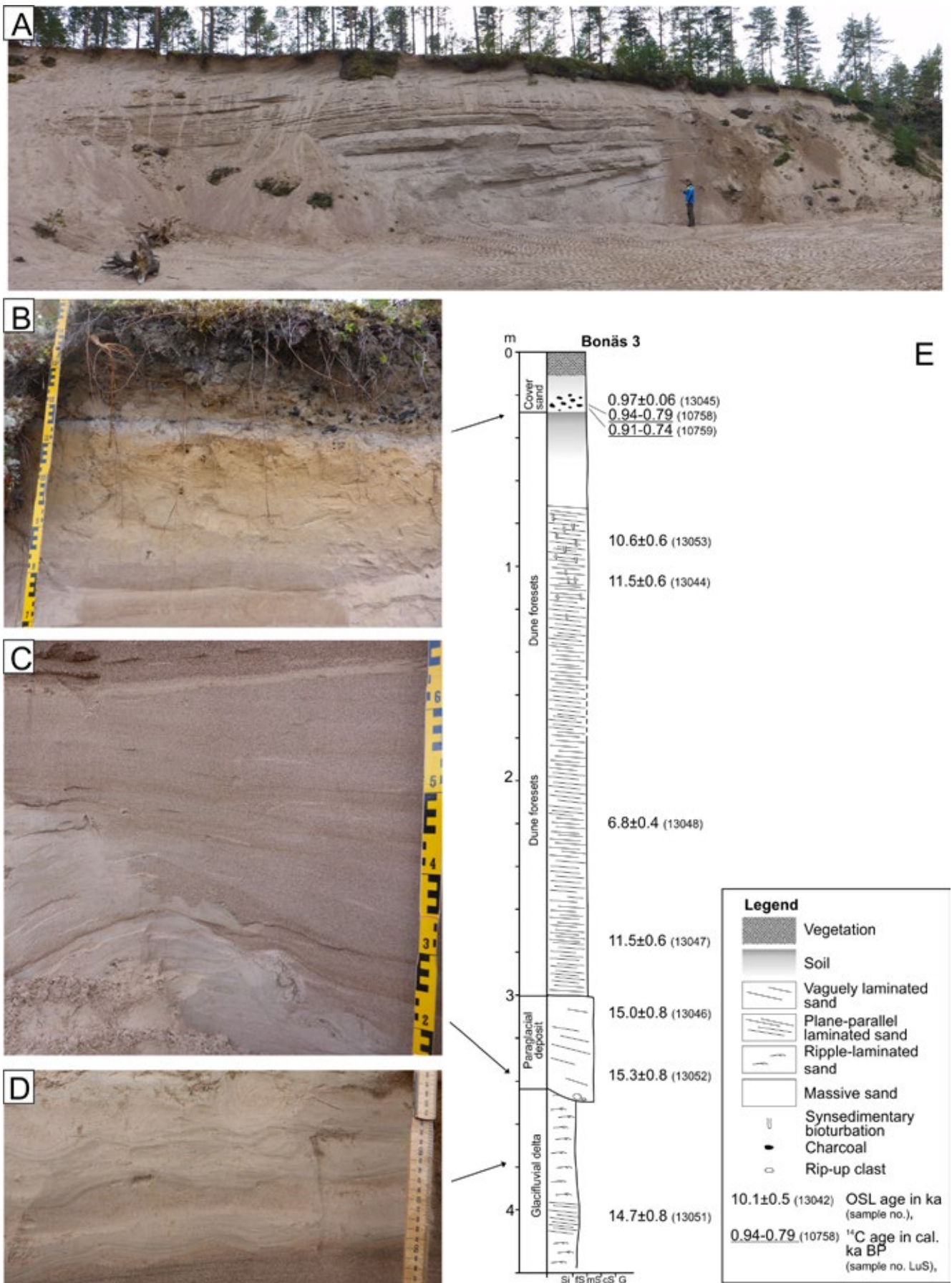
Fig. 12. Bonäs 3 (61.100°N, 14.470°E) is one of our key sites in Dalarna. Here glacifluvial, paraglacial, dune/interdune sand and coversand are found in superposition. A. Overview of the exposure in the sandpit. B. Present soil and a palaeosol in the uppermost part of the section. C. Erosional boundary between glacifluvial (light grey, lower left) and paraglacial (light brown, upper right) deposits. D. Glacifluvial ripple-laminated sand. E. Composite log (modified from Alexanderson & Bernhardson, in press).

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ing percentage of aeolian-type grains (matte partially- and well-rounded). Finally, there are more than 50% of aeolian grains in the coversands. This is certainly the result of multiple aeolian reworking, in which the same deposits were exposed to repeated abrasion.

Värmland

Brattforsheden

The Brattforsheden dune field (Fig. 13), which has been described by Hörner (1927), was investigated during a previous SGU-funded project led by Alexanderson and the results have been published (Alexanderson & Fabel 2015). Within this project we have complemented the previous results with GPR-profiles across a few dunes, including one blow-out feature with a prominaent soil (Fig. 14A), and with additional sedimentological observations at old sites and targeted OSL sampling to address the timing of re-activation events.

Most likely due to rainy weather and variable wetness in the ground, the GPR profiles were unfortunately not as informative as expected. Excavated sediment exposures show that the sediments in the dune forms are massive or vaguely laminated sand (Fig. 14B), which confirm previous observations. OSL samples from sand below the main soil at the Långbromana dune range in age from 10 to 7 ka. Sand in the blow-out is dated to ~600 years, with radiocarbon ages of charcoal of less than 300 cal. yr BP.

A combination of all possible types of quartz grains is observed in sediments at Brattforsheden and the following groups occur: non-abraded ('fresh') and broken grains, as well as aeolian-(matte) and fluvial-(shiny) type grains. We have not observed significant differences between aeolian and glaciofluvial settings. This means that wind transport was rapid and did not result in serious grain abrasion.

Sörmon and Törnemon

Two areas west of Karlstad have been studied: the delta at Sörmon and an individual dune at Törnemon (Fig. 15). At Sörmon, a large set of parallel ridges are interpreted as littoral sand bars modified by wind to form dunes (Persson 1948; Blomquist 1969; Fredén 2000), see also Fig. 16A. Sediments were logged and sampled in two abandoned sand pits east of the Sörmon nature reserve. Apart from the upper meter, which is massive, the sediments – fine-medium sands – are finely laminated and homogeneous down to at least 2.7 m depth. Preliminary OSL ages are 10.5-10 ka.

Törnemon is Värmland's highest dune and a radiocarbon date of charcoal from below the dune

Fig. 13. Brattforsheden site map. © Lantmäteriet (i2012/927)

indicates it is younger than 2300 years BP (Fredén 2000). The dune sediments were documented in a small sandpit and three OSL-samples were taken. The fine-medium sand is vaguely laminated, in many places the lamination is disturbed and sediments appear massive (Fig. 16B). Preliminary OSL ages are ~2.5 ka.

Närke and Östergötland

Kumla area

Here, aeolian deposits associated with raised beach ridges are found at several places (SGU 2016). Three sites (Alltorp, Kulan and Bodatorp) at different elevations within one of these beach-ridge plains east of

Fig. 14. A. A prominent buried soil in the blow-out in the Långbromana dune, Brattforsheden. B. Indistinctly laminated dune sand in Nabbmanen, Brattforsheden.
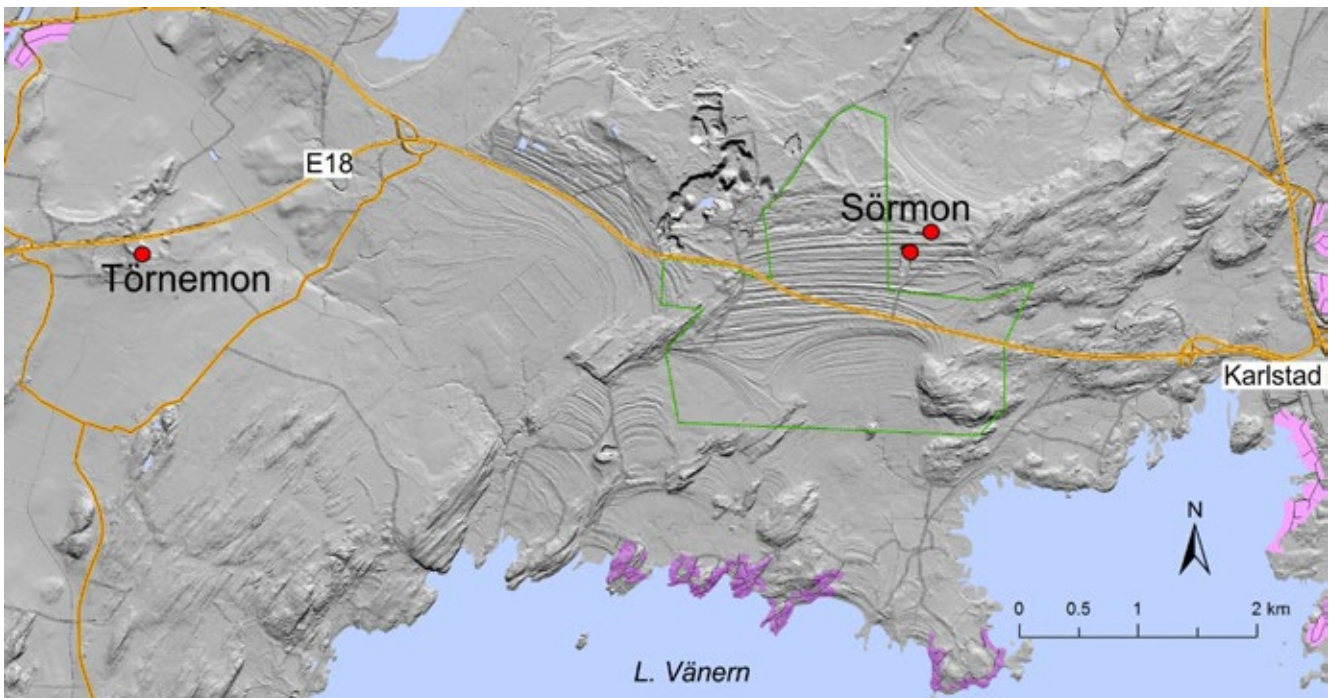
Fig. 15. Sites near Karlstad shown on a hill-shade model. LiDAR and map data © Lantmäteriet (i2012/927).

Fig. 16. A, above. View of the sand bars/dunes at Sörmon. B, below. Laminated sand disturbed by bioturbation in the dune at Törnemon.

Fig. 17. Sites in Närke and Östergötland. © Lantmäteriet (i2012/927)

Kumla were investigated (Figs. 17, 18). The aeolian sands are massive, fine-medium sand and at Kulan two thin palaeosols are found at 50-70 cm depth. No OSL ages are yet available but preliminary data suggest that ages become younger with lower elevation and that the sand above one of the palaeosols is significantly younger than the lower sand.

Lerbäcksmon

Aeolian deposits have been mapped in the Lerbäck area (SGU 2016), including a sparse dune field – Lerbäcksmon – described by Bergqvist (1981). The most prominent dunes are situated at or south of Lerbäck (Figs. 17, 19) and their wavy or crescentic crests are generally oriented NE-SW or E-W. A few road cuts and household sand pits allowed documentation of
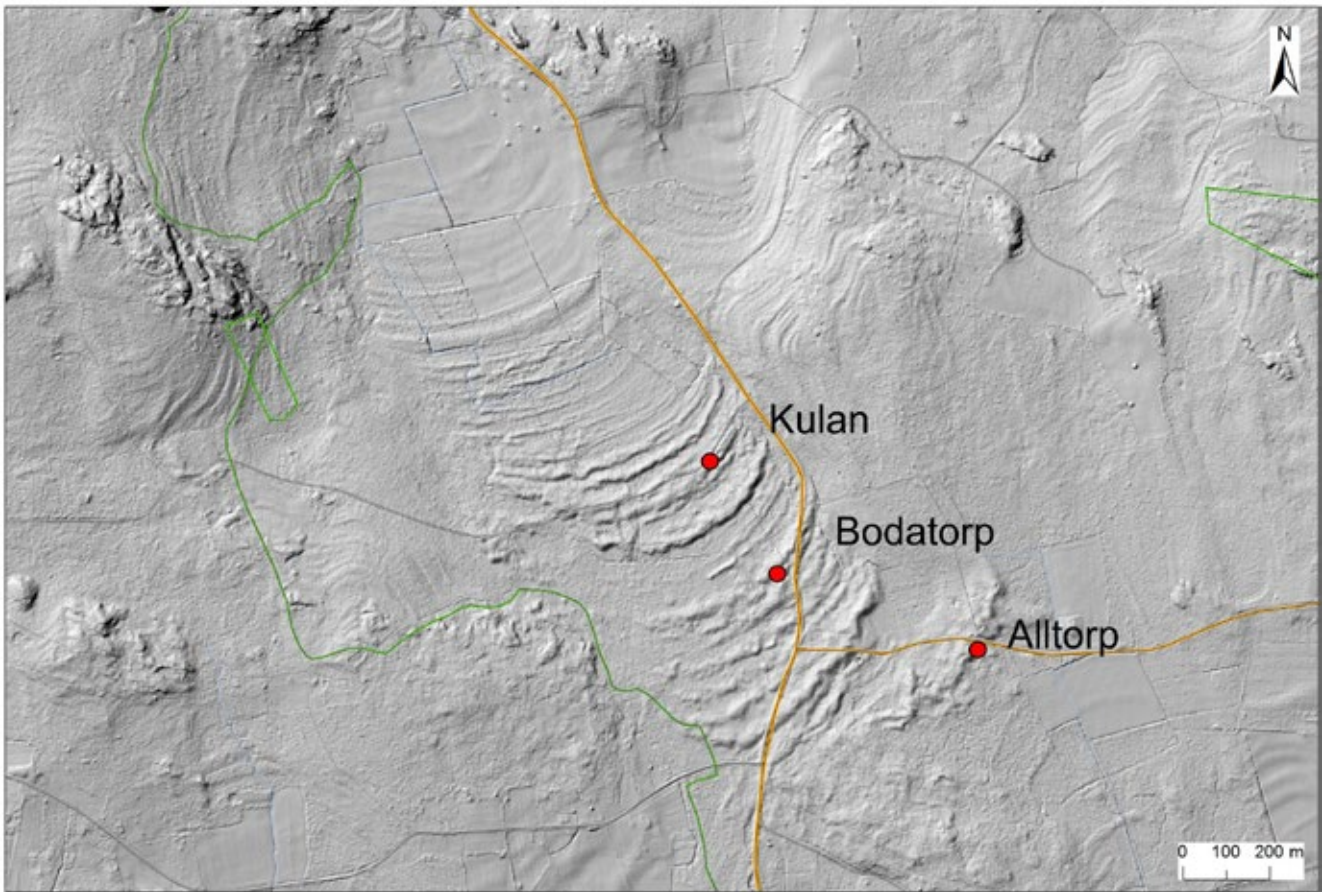
Fig. 18. Raised beach ridges with dunes north of Kismo, east of Kumla. The sampled sites Alltorp, Kulan and Bodatorp are marked with red dots. LiDAR and map data © Lantmäteriet (i2012/927).

Fig. 19. One of the dunes in the Lerbäcksmon dune field.

the dune sedimentology and sampling for OSL dating. The large dune within the Vissbodamon nature reserve north of Lerbäck (Fig. 17) was visited but not sampled. Two samples of glacilacustrine sands were, however, taken in a nearby sand pit, for comparison of ages and luminescence characteristics.

The aeolian dune sand is well-sorted fine-medium sand, mainly thinly plane-parallel laminated but partly more massive, particularly in the upper part. Preliminary OSL data suggest the dunes were formed ~10-9 ka ago, while the glacilacustrine sands appear very old (>200 ka).

Mjölby area

The area contains a number of small and isolated dunes, most of which are fairly straight-crested and oriented E-W (Johansson 1979). No sediment exposures were available but by digging and coring two dunes were sampled for OSL dating. Two samples were taken from a small crescentic dune at Öjebrotorpen near the Svartån Stream NE of Mjölby and one sample from a low straight-crested dune at Mjölbyfältet N of Mjölby (Figs. 17, 20). No OSL ages are yet available.

Västergötland

Skara area

A number of small dunes or mounds are found in this area (SGU 2016), some of the dunes are crescentic or parabolic. Four sites with sediment exposures were studied: parabolic dunes at Skogalund and Nyängen, a N-S oriented crescentic dune at Bäckåsen and an irregular dune at Karstorp (Fig. 21). The sediment is well-sorted, massive or laminated fine-medium sand with evidence of bioturbation (Fig. 22). No OSL ages are yet available but preliminary data suggest that the dunes in this area are of roughly the same age.

Skövde area

A few straight-crested or crescentic dunes are found in this area, as well as coversand and irregular mounds mapped as aeolian in origin (Påsse & Pile 2016; SGU 2016). Small cuts along paths were investigated in a crescentic, likely parabolic dune at Laggartorp, in a mound at Skövde airfield, and in two relatively straight-crested dunes at Valstaberg and Stenebacken (Fig. 21). Below more or less well-developed soils the sediment consists of massive fine-medium sand (Fig. 23). No ages are yet available for these sites.

Fig. 20. A low, straight-crested dune in Mjölbyfältet.
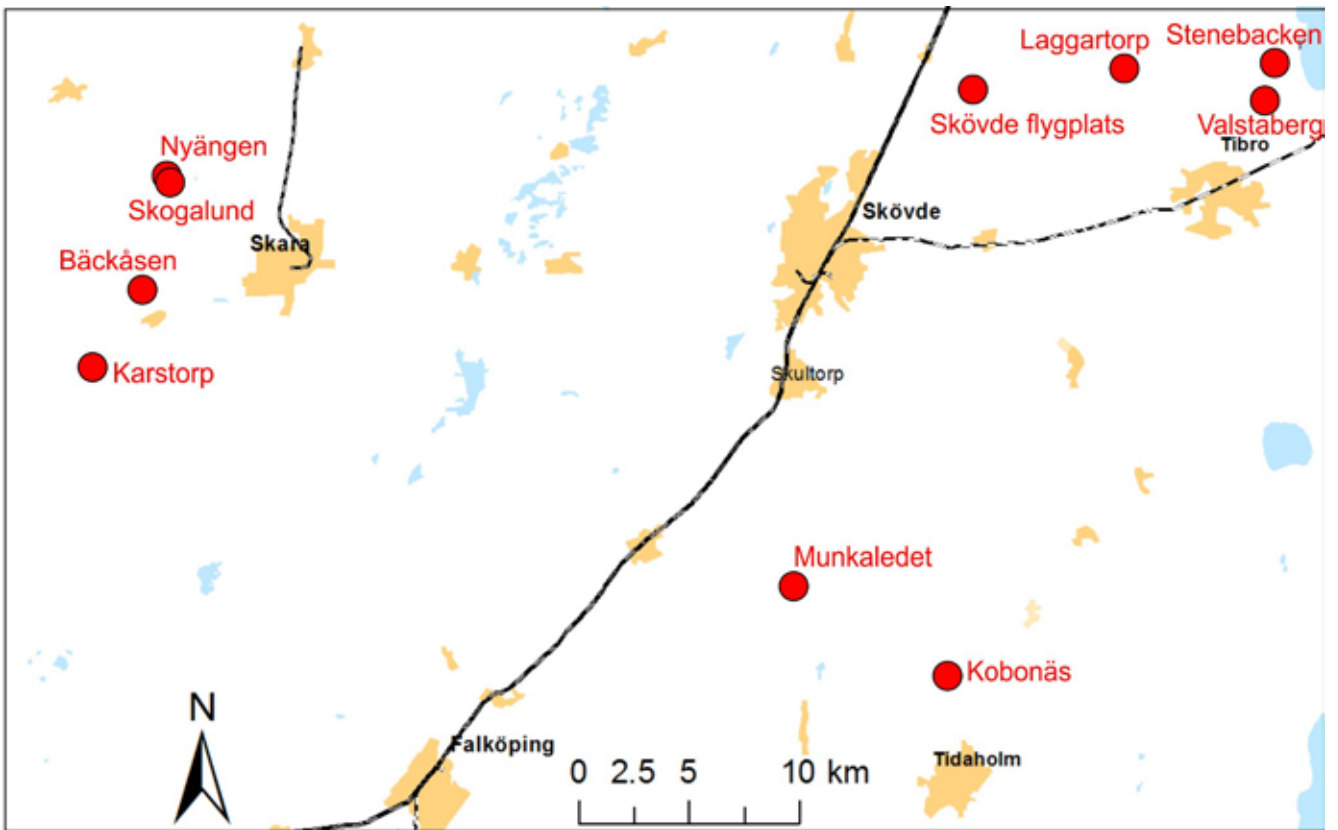
Fig. 21. Sites in Västergötland. © Lantmäteriet (i2012/927)

Fig. 22. Laminated and bioturbated sediment in the dune at Karstorp.

Fig. 23. Massive sand in straight-crested dune at Valstaberg in the Skövde area. The X's mark the spots for the OSL samples.

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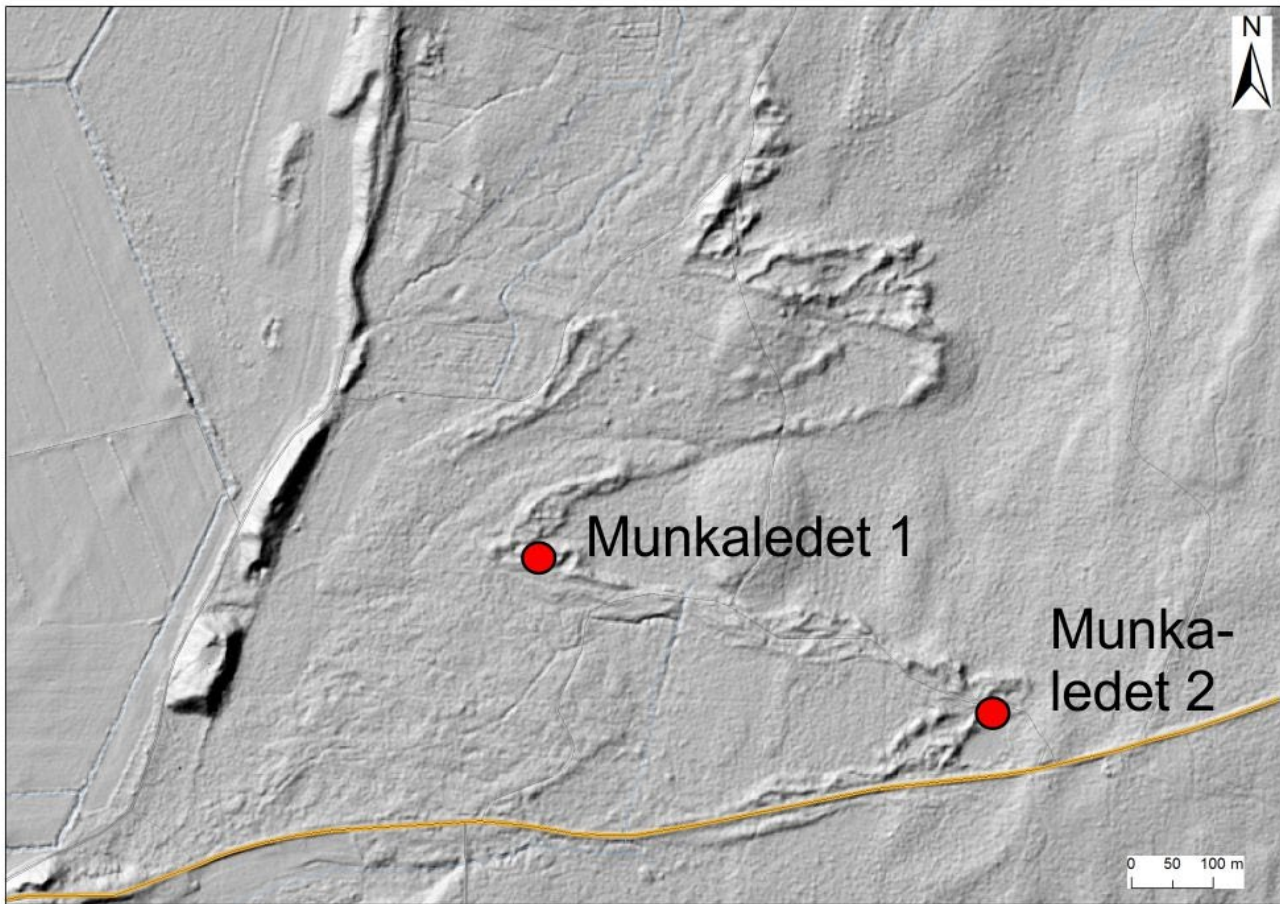
Fig. 24. A, above. The highly crescentic dune at Munkaledet. An esker is also seen in the left-hand side of the image. LiDAR data © Lantmäteriet (i2012/927). B, right. The present soil and one of the palaeosols within the dune sand at Munkaledet.

Tidaholm area

Aeolian deposits are found in this area (SGU 2016), including a few irregular, partly parabolic dunes. Hand-dug pits and small road cuts were used to access the dunes' interior at three sites: a N-S oriented straight-crested dune at Kobonäs and two locations on a highly crescentic dune at Munkaledet (Figs. 21, 24A). The sediment in the dunes is well-sorted, massive fine-medium sand. At Munkaledet, at least two weak buried soils are found 30-50 cm and 80 cm below the surface (Fig. 24B). No OSL ages are yet available but preliminary data suggest the Kobonäs dune and the lowest sand in the Munkaledet dune are roughly contemporaneous, likely 8-6 ka old, while sand above the soils is in the order of ~2 ka and ~1 ka old.

Småland

Store Mosse area

A number of long and winding dunes stretch across the large bog of Store Mosse, and in the vicinity there are also coversand deposits (Svedlund 2006; Persson 2008). Two sites near Store mosse have been studied:

Bredaryd and Sandliden (Fig. 25A). Bredaryd was visited together with a group led by Malin Kylander from Stockholm University, who study dust deposition in the bog (Kylander *et al.* 2013).
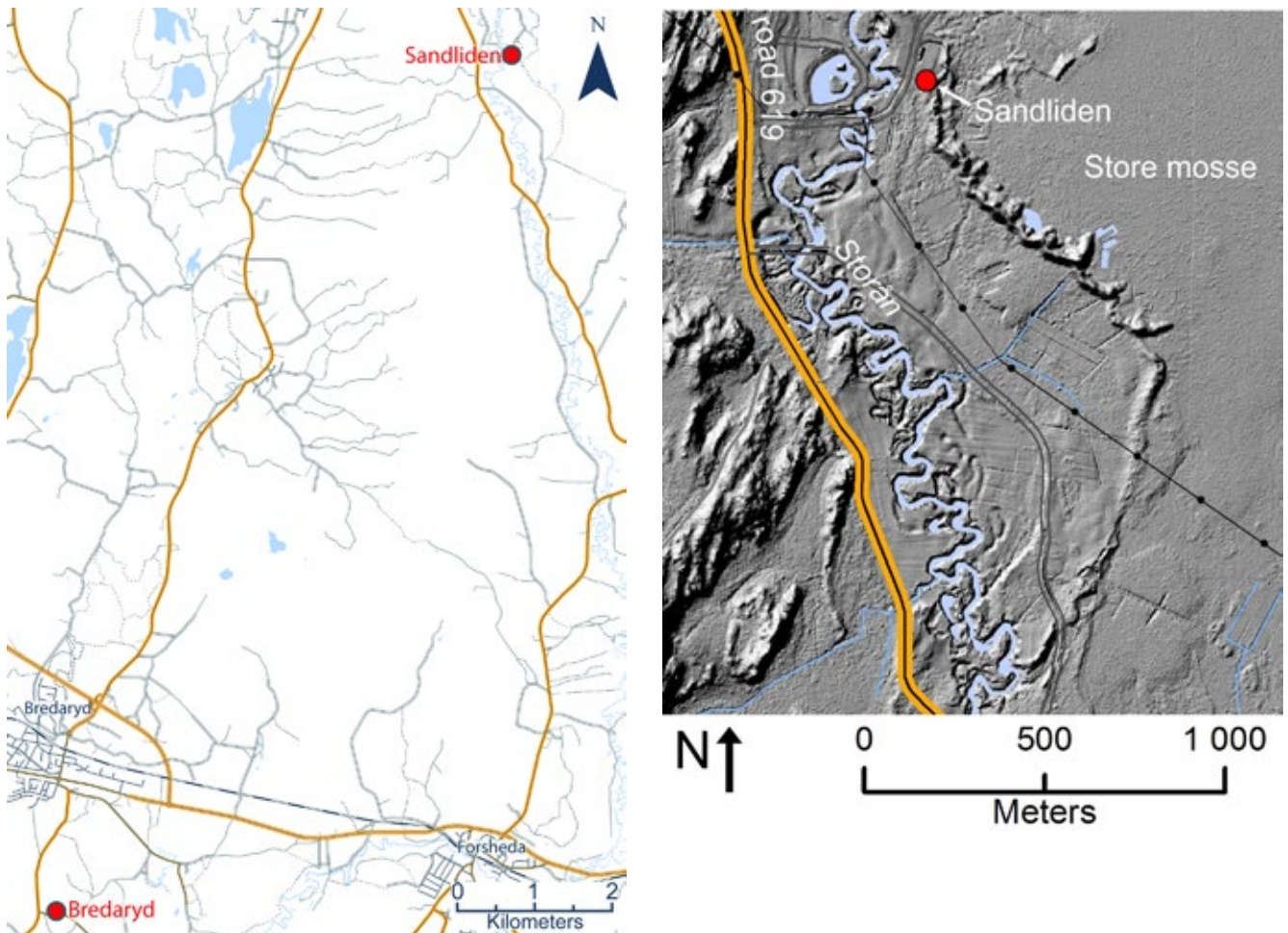
Fig. 25. A. Sampled locations in the Store Mosse area. B. The dunes at Sandliden shown in a hill-shade model. © Lantmäteriet (i2012/927)

Two OSL samples were taken from a poorly exposed road cut in a dune heap surrounded by a predominantly coniferous forest at Bredaryd. At Sandliden an exposure in the northernmost of several connected, small crescentic dunes was logged and sampled for OSL (Fig. 5, Fig. 25B). The sediment within the dune is fine-medium sand that is laminated and shows evidence of both syn- and post-sedimentary bioturbation. The uppermost part is massive. The OSL ages are c. 12-11 ka in the lower part and ~7 ka in the upper, massive part.

Skåne

Ängelholm

The coast in the inner part of Skälderviken, near Ängelholm (Fig. 26), is characterised by sandy beaches with foredunes. The area is subject to ongoing coastal erosion, which is studied by Caroline Fredriksson at Water Resources Engineering at the Lund Technical University (LTH). We contribute with geological knowledge to her project.

Historical records, maps and airphotos show that some dune ridges inside the presently active foredune were created in the 18th century as a response to stop erosion and sand drift (Björnfors 2016). The coastal erosion is stronger in the northern part of the coast (close to Ängelholm), while accumulation dominates in the south. This is reflected in the geomorphology and sedimentology of the foredune and beach (Björnfors 2016). OSL samples of the foredune (Fig. 27) have been taken and preliminary data show it to be quite young.

Blentarp and the Vomb basin

Overlying the glacifluvial and glacilacustrine sediments in the Vomb basin there are relatively extensive aeolian deposits, a few dunes but mainly coversands (Daniel 1986). In a gravel pit outside Blentarp (Fig. 26) coversand on top of glacilacustrine deltaic deposits is exposed and has been documented and sampled. The coversand, which is massive, fine-medium sand and up to ~2.5 m thick, contains at least two palaeosols (Fig. 28).

The sands were dated by OSL on quartz and IRSL on feldspar, and charcoal from one of the palaeosols was dated by radiocarbon. The different types of

Fig. 26. Map of Skåne with our sites. © Lantmäteriet (i2012/927)

ages agree and show that the coversand was deposited during five episodes: at ~15.2 ka, at 14.5-13.0 ka, at 1.9-1.7 ka and more recently at ca 400-300 and 200-160 years ago (Shrestha 2013).

The glacilacustrine deltaic deposits are represented by medium- to coarse-grained, either well- (deltaic deposits) or poorly-sorted (channel deposits) sands. These have positively skewed grain-size distributions. The aeolian cover, in contrast, is rather fine-grained, moderately-sorted and in all samples with negative skewness.

A core from Lake Vomb has been retrieved (Ljung *et al.* 2014) as part of project initiated by Anna Broström (National Heritage Board) and Karl Ljung

(Dept of Geology, Lund). Alexanderson has become involved in this work since the core may be used to, for example, identify sand-drift events in the Vomb basin. The core has been XRF-scanned but the data have not yet been analysed.

Kristianstad plain

A set of prominent coastal foredunes and stabilized dune complexes occur in the Kristianstad plain. Four sites near Åhus and Vittskövle have been investigated: two foredunes (present-day and relict, respectively) at Åhus 1 and 2 (Figs. 26, 29), a parabolic dune situated 0.5 km from the present-day shoreline at Åhus, and, finally, a straight-crested dune and its underlying sediments at Vittskövle.
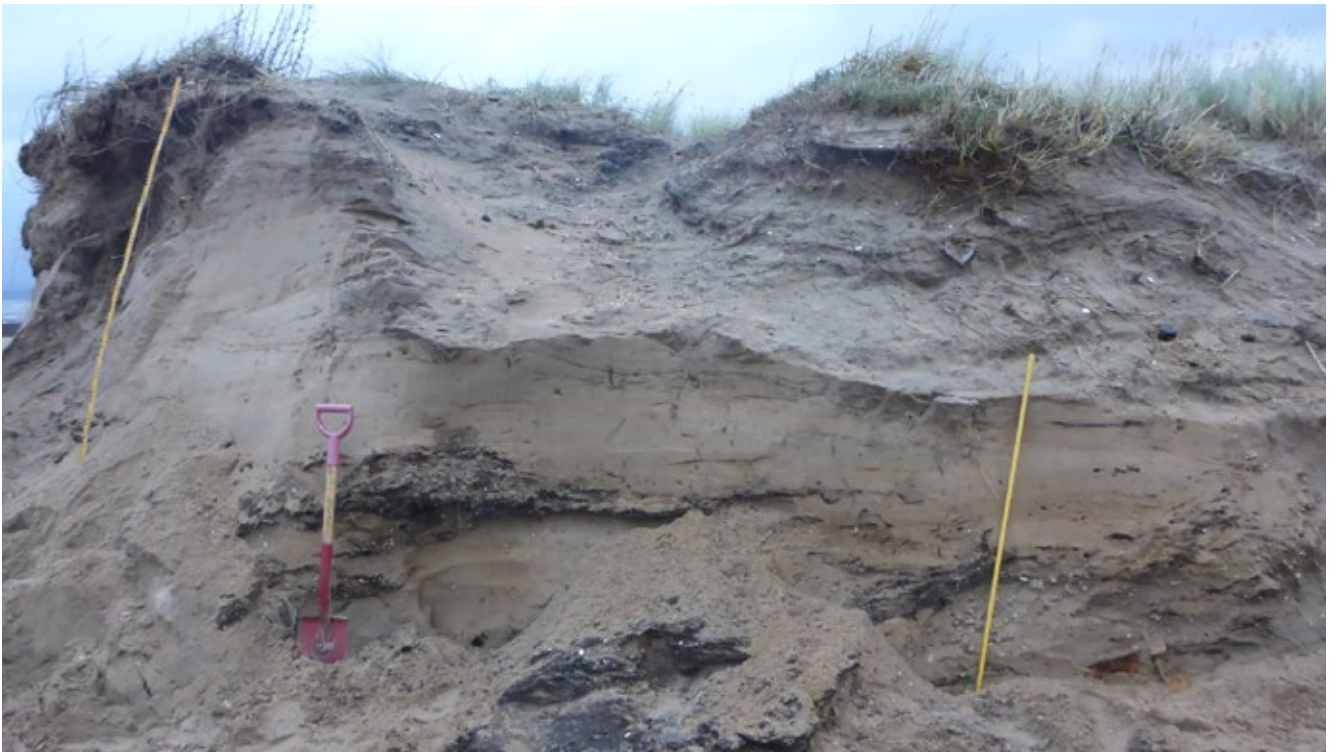
Fig. 27. An exposure caused by storm waves in the foredune at the northern part of the inner Skälderviken. The dune sand contains shells, sea weed and plastic, the latter attesting to its young age.
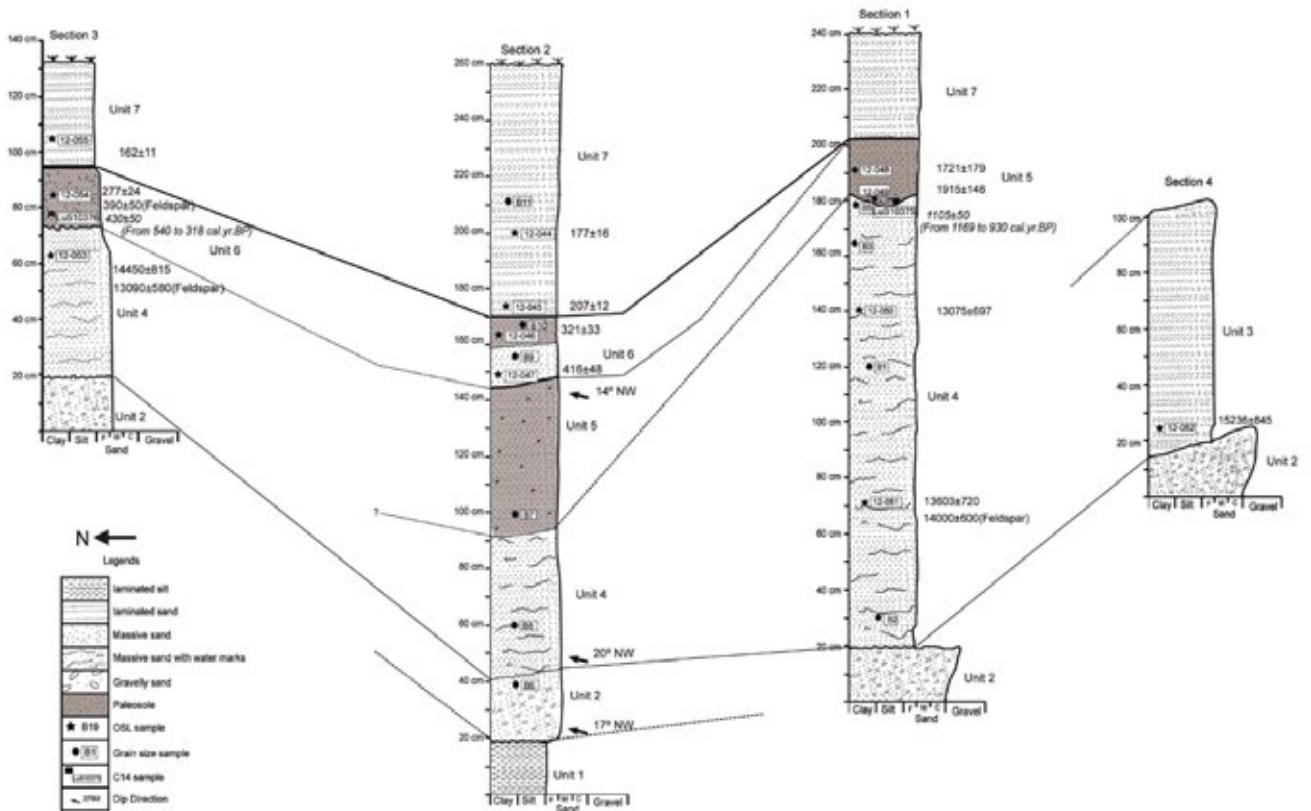
Fig. 28. Coversands and palaeosols in the Blentarp gravel pit. From Shrestha (2013).

Altogether ten OSL samples were taken from aeolian sand and one radiocarbon sample from a buried palaeosol (Vittskövle). These ages reveal coastal-aeolian deposition during one older littoral phase at 11.6 ka and at least two events of later sand mobilisation: (1) in the inland dunes at AD 1686-1799, and (2) in the foredunes at the beginning and in the end of the 20th century. The palaeosol formed AD 1476-1637 (Fig. 30) and partially corresponds with a short and abrupt climate warming during the Little Ice Age (Kalińska-Nartiša *et al.* in press).

Multi-proxy sedimentary methods have been applied to these aeolian-coastal deposits and reveal a general trend of sediment transformation and pathways. For example, the littoral (Fig. 31A-C) and foredune (Fig. 31D-F) sediments show similar grain features and only a slight transformation in grain-size from littoral to foredune deposits can be seen. The sand in the parabolic (Fig. 31G) and straight-crested (Fig. 31H) dunes seems, in contrast, to originate from immature glacilacustrine sediments (Fig. 31I) on the Kristianstad plain (Kalińska-Nartiša *et al.*, in prep.).

Fig. 29. Present-day foredune (covered by grass) and relict foredune (covered by trees) at Åhus 1 and 2 sites (after Kalińska-Nartiša et al. in press).
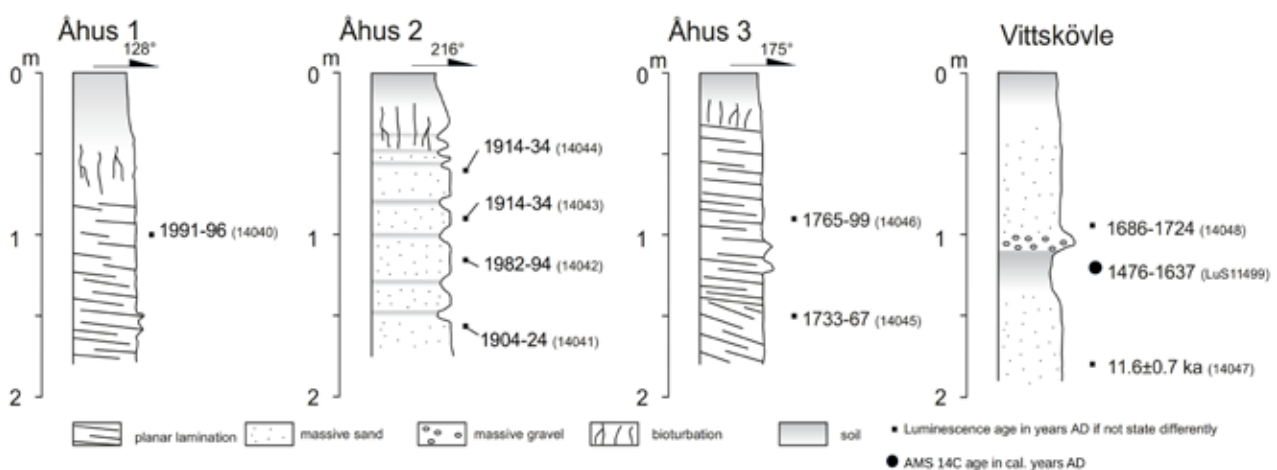
Fig. 30. Sedimentary logs, OSL and AMS-14C ages from the sites Åhus 1-3 and Vittskövle (modified from Kalińska-Nartiša et al. in press).
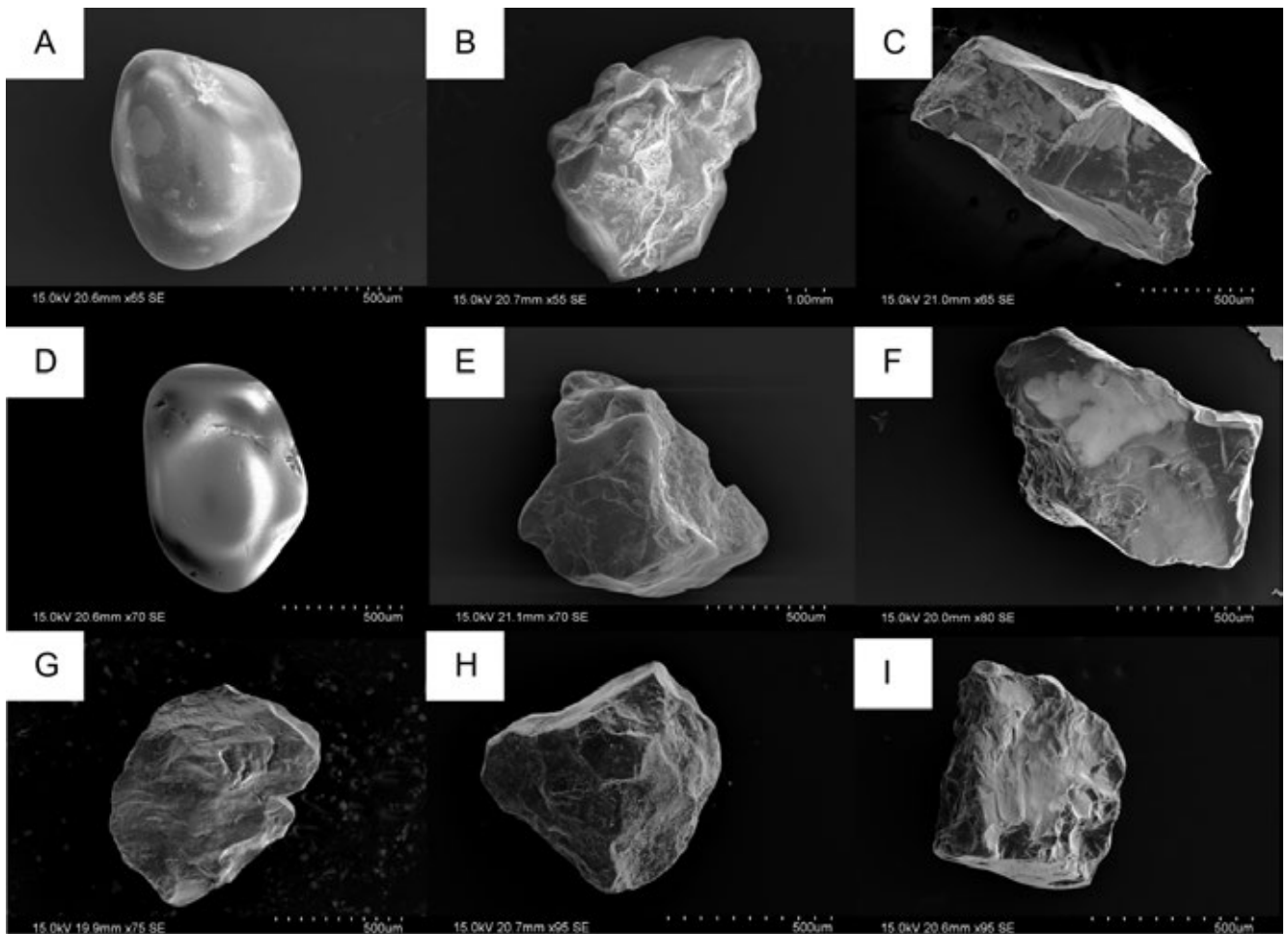
Fig. 31. Explanatory images of quartz sand grain shape and character of its surface from the Kristianstad plain: A-C – types of quartz grains typical for littoral sediments: A. Well-rounded shiny grain with low relief; B. Partially rounded with medium relief; C. Non-abraded with sharp edges and fresh surfaces; D-F – types of grains typical for foredune: D. Well-rounded shiny grain with low relief; E. Partially rounded grain with medium relief; F. Non-abraded grain with fresh surfaces and only slightly rounded edges; G. Partially-rounded grain with sharp edges and medium relief (parabolic dune); H. Cracked grain with both sharp and partially rounded edges and medium relief (straight-crested dune); I. Cracked grain with both sharp and partially rounded edges and medium relief (glacilacustrine sediments).

Publications and presentations

A number of papers, presentations and student theses have come out of the project and more are in progress. As of August 2016, we have two peer-reviewed papers published or in press (available online), one submitted and two more than half-finished manuscripts. Data from this project have also been included in ten conference presentations, three other presentations and one excursion guide. Four student theses (MSc, BSc) have been completed and one PhD thesis and one bachelor thesis is ongoing. For full list see App. 3.

Data management

Primary data have been archived on servers at the Department of Geology together with documentation of sites, methods, sources of error and other relevant information and can be made available upon request. A publically available GIS-based OSL database hosted at the Lund Luminescence Laboratory is still aimed for but will not be available within a year. Final data will be made accessible through the PANGAEA information system (https://www.pangaea.de/) and we are also now looking into the possibility of including our data in the 'The INQUA Dune Atlas chronologic database' (Lancaster *et al.* in press).

Discussion

Methodological advances and improved competence

The use of LiDAR data for geomorphological investigations has proven to be an efficient method for mapping a dune field, especially compared to previous methods of remote sensing (cf. Bernhardson & Alexanderson submitted). In Bernhardson and Alexanderson (submitted) we show that LiDAR data together with GIS software allows quick and precise investigations of a whole dune field; everything from geomorphological categorization to reconstructing palaeowind environment. Since the whole of Sweden soon will be mapped by LiDAR (Lantmäteriet 2015) the future for more detailed geomorphological investigations looks very promising.

For some of our sites we have worked with very young material (less than a few hundred years). In many cases such material requires special treatment in OSL dating due to risk of thermal transfer (cf. e.g. Rhodes & Bailey 1997) and also to be able to resolve the low doses. The OSL reader at the Lund Luminescence Laboratory is adapted for samples with relatively high doses (i.e. old material) since it has a laboratory dose rate of ~0.15 Gy/s. This makes it difficult to measure very low-dose samples, which require irradiation times of less than a few seconds (cf. Markey *et al.* 1997; Przegiętka & Chruścińska 2014). A laboratory intercomparison with the OSL reader in Malmö, which has a much lower laboratory dose rate (~0.00087 Gy/s), did indeed show a significant age difference for some young samples (Kalińska-Nartiša *et al.* in press). With the Malmö reader we were able to better resolve the ages of young samples, but we have also in the process discovered ways in which we can, at least partly, also use the Lund reader for young samples.

The OSL work with the different types of material in this project, both regarding sediment age and quartz characteristics, has led to increased competence in the staff of the OSL laboratory. Some samples have been easy to measure, and for these we have been able to further explore their possibilities, e.g. looking at range-finder dating (Roberts *et al.* 2009) and bleaching issues (Alexanderson & Bernhardson in press). Other samples have been tricky, mainly because of poor luminescence characteristics (cf. Alexanderson & Murray 2012), and we have had to spend much time in finding ways to analyse them, which although sometimes frustrating leads to a better understanding of luminescence in general.

Additionally, in work closely related to this project, geology students have been trained in sedimentology, geomorphology, ground-penetrating radar and OSL dating.

Timing and style of aeolian events

The majority of the (so far) dated aeolian deposits were deposited close in time to the deglaciation of the area in question. The timing of the earliest aeolian deposition thus becomes younger towards the north, from ~15 ka in Skåne to 11-10 ka in Dalarna (Fig. 32). Particularly, the larger dune fields seem to be closely related to deglaciation, as suggested already by early investigators (Högbom 1913, 1923; Hörner 1927), but data from e.g. Västergötland and Skåne suggest that some single dunes formed during the Mid- and Late Holocene as well. Most of the 'non-deglacial' deposits at our sites are otherwise coversands or coastal dunes (Fig. 33).

This early sand-drift phase, which at most of our sites involved dune formation, seems to have lasted around 1000-2000 years. The Siljan area with Bonäsheden and Skattungheden are so far the most well-dated sites and the many OSL ages from there indicate continuous dune formation for at least 1500 years (Alexanderson & Bernhardson in press); similar to Brattforsheden in Värmland (Alexanderson & Fabel 2015). At other sites, such as Blentarp in Skåne (Fig. 28; Shrestha 2013), the few somewhat scattered older ages may indicate one continuous event or separate events; the current dataset is too small to say for certain.

Dune formation in recently deglaciated areas is not unexpected. In such pro-, para- and periglacial areas sand drift is common and closely related to the cold climate, strong katabatic winds, little or no vegetation and plenty of sand that characterise these settings (e.g. Ashley 1985; Seppälä 2004; Bullard & Austin 2011; Pye & Tsoar 2012). Sand drift may start immediately after the glacier or ice sheet has retreated from the area, or be somewhat delayed due to that land first has to be uplifted out of the sea (such as the dune fields formed on deltas in Sweden) or for (glacial) lakes to drain (Hilgers 2007).

Previously it has been assumed that dunes were stabilised shortly after vegetation immigrated and the duration of dune-forming events has been suggested to be ~300-400 years based on rates of isostatic uplift (e.g. Högbom 1923). Our OSL ages suggest that dunes were active for longer, and also after vegetation became established (Fig. 32). There is some uncertainty given the resolution of most OSL ages of that age range (c. ±0.5 ka), but still in the case of both Bonäsheden/Skattungheden and Brattforsheden the youngest dune OSL ages are significantly younger than the oldest (acceptable) ages, by at least 400-800
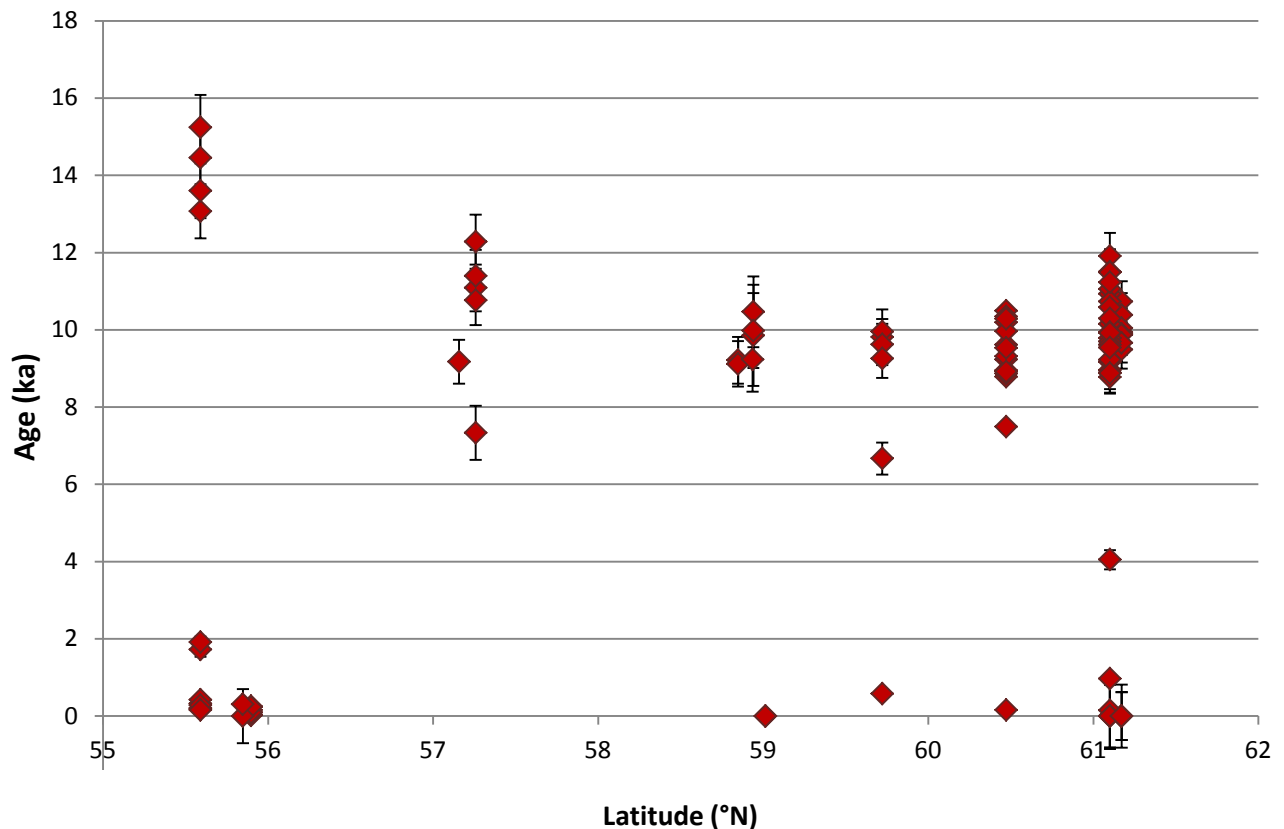
Fig. 32. Plot of OSL ages of aeolian deposits along a transect from the southernmost to the northernmost of our sites in Sweden. The decreasing age towards the north reflects the later deglaciation there, and the subsequently younger aeolian activity.

years when errors are included (Alexanderson & Fabel 2015; Alexanderson & Bernhardson in press).

During this relatively long time, wind patterns changed, vegetation cover increased etc. but still dunes were apparently active. However, there seems to have been changes in the type and orientation of dunes. For example, our detailed geomorphological mapping and many OSL ages from Bonäsheden allow us to distinguish different phases in the development of that dune field, from large NE-SW oriented to smaller E-W oriented dunes (Alexanderson & Bernhardson in press; Bernhardson & Alexanderson submitted).

Following the initial stabilisation, the dunes in these large dune field show little evidence of transformation during later events. The transverse, crescentic dunes are not generally reworked into secondary dune types such as parabolic dunes and their internal structures reveal almost no major boundary surfaces (e.g. Fig. 10). There are few buried palaeosols and no significantly younger OSL ages have been retrieved from dunes in Dalarna and Värmland. Any younger Holocene events seem to have resulted only in coversand being draped over the dunes. This development is similar to what has been described for boreal dune fields in the Great Plains in North America (Halfen *et al.* in press) and makes these dunes relatively rare records of Early Holocene aeolian landscape formation (cf. Högbom 1923). In other similar areas dunes have

been partially or more or less completely reworked during the Holocene (e.g. Seppälä 1972; Halfen *et al.* in press).

South of our main area (Värmland-Dalarna), the situation is, however, different, and we get ages also from the Mid- or Late Holocene (Fig. 33). As can be seen in Fig. 33, most of the younger ages are less than 500 years and so far there are only few older, scattered ages from the Mid-Holocene. This limited data set makes inferences about causes of sand drift during these events speculative and so we will only make a tentative comparison to other records from northern Europe at this stage. Some of these ages fall within NW European Holocene storm periods (HSP; Sorrel *et al.* 2012) or correspond to periods of strong sand-drift recorded in e.g. Denmark (e.g. Clemmensen *et al.* 2009) (Fig. 33). Taking our ages at face value, the aeolian deposits studied by us seem to record HSP II (4500-3950 cal. a BP), HSP IV (1900-1050 cal. a BP) and HSP V (600-250 cal a BP). These storm periods are interpreted as due to changes in the oceanic and atmospheric circulation pattern in the North Atlantic (Sorrel *et al.* 2012) and the Swedish aeolian deposits from these periods may thus be a result of a regional, climatic cause.

There are also deposits aged ~7.5-6 ka (Fig. 33, plus preliminary ages from Västergötland and Småland). These younger deposits are coversands or
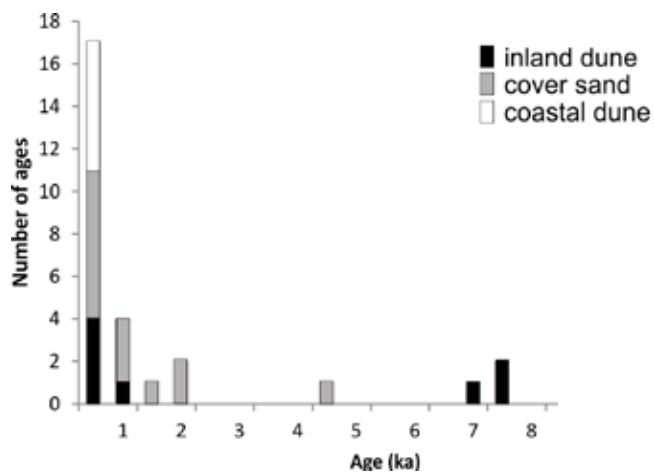
Fig. 33. Histogram of ages (OSL, C14) younger than 8 ka classified by origin: inland dune, coversand and coastal dune.

dunes that are mainly single dunes and not part of a dune field. The preliminary ages from Västergötland are supported by the relative dating by Lundqvist (1920), who based on pollen analyses suggested an early sub-boreal time (~6 ka BP) of dune formation in this area. These ages do not correlate to any of the storm periods of Sorrel *et al.* (2012), but rather fall into the end of the Holocene optimum. During this time, drier conditions are indicated by increased dust deposition and lower lake levels in southern Sweden (e.g. Digerfeldt 1988; Kylander *et al.* 2013), which suggest a regional rather than a local cause. Once we have the final data we will certainly look more into the context and causes of these deposits.

The ages of our youngest deposits partly overlap with HSP V, with the Little Ice Age and with a phase of intensified human impact (through agriculture, foresting etc.). This makes it interesting but difficult to identify causes behind these events. Are they climatic or anthropogenic? We need to work more with our data and compare to other records to find out. Our so far best record of the youngest events is from Skåne (Fig. 34). There, inland dunes were formed between AD 1686-1799 on the Kristianstad plain and this corresponds with the coldest phase of the 'Little Ice Age' (Lamb 1984), as well as with ages of coversand in the Vomb basin (Blentarp). In the Kristianstad area, sand mobilisation was likely due to forest destruction during the siege of Kristianstad in 1677-1679 or/and intense land cultivation, which is largely supported by historical records. For example, no forest is marked in the Vittskövle area on maps from that time (Burman 1684). From other regions we know that this was also a time with a peak in storminess and a general increase of aeolian activity (Madsen *et al.* 2010; Fedorowicz *et al.* 2012; Dobrotin *et al.* 2013; Sydor *et al.* 2015).

The youngest (20th century) OSL ages that we so far have obtained are coming from two foredune ridges at Åhus in Skåne (Fig. 30). These coastal dunes

are influenced by partly other factors than the inland dunes, e.g. sea-level changes, and the records are not directly comparable. However, it can be noted that sand ridges of similar age are found elsewhere in the Baltic Sea (north-western Poland; Reimann *et al.* 2011) and also on the west coast of Denmark (Madsen *et al.* 2007).

We have seen some differences in the sedimentology of the aeolian deposits in the studied areas. Grainsize wise there is little variation, most dune sands consist of fine-medium sand. Regarding the quartz grains, they show few aeolian characteristics in the older dune sands, which suggest only minor re-working from the source material, perhaps due to short transport distances. This agrees with other studies, where dune sands, although with a high content of aeolian quartz grains, are similar to their potential source sediments (Kalińska-Nartiša & Nartišs 2016) or carry impact of local factors (Woronko *et al.* 2015). Aeolian features on the grains become more prominent in the cover sands, which have likely been re-worked at least once more from the dune sands and thus are more texturally mature.

Structurally, we see a difference between the dunes in Dalarna and those farther south, e.g. in Brattforsheden. The Dalarna dunes, as well as those in Starmoen in Norway (Alexanderson & Henriksen 2015), are dominated by distinctly laminated sediments with a conspicuous type of synsedimentary bioturbation (Fig. 11). We interpret this as wind-ripple migration is a dominant process on both windward- and lee sides of dunes (cf. Fryberger & Schenk 1988), together with grain fall on the lee side. It can be noted that Högbom (1923, p. 151) describes the dune sand in Bonäsheden (the Mora field) as indistinctly stratified. However, from the text it appears that he mainly (only?) studied shallow sediment exposures, and we also found the upper 0.5-1 m to be massive or vaguely laminated, while deeper sediments are definitely laminated (Fig. 11A).
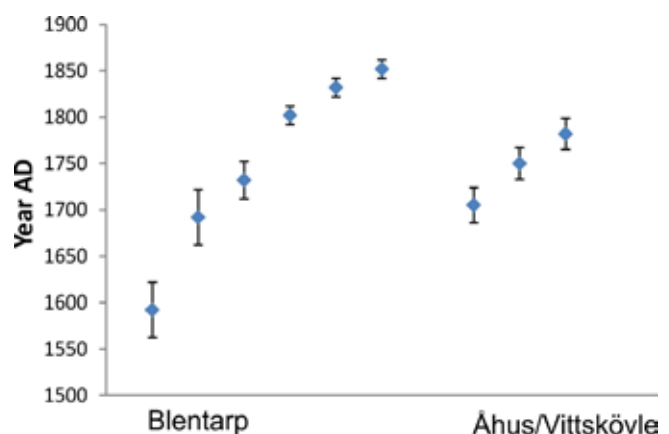
Fig. 34. Ages of young inland aeolian deposits at Blentarp, Åhus and Vittskövle in Skåne.

In contrast, at some sites in Värmland and Västergötland sites for example, the dune sand is massive or vaguely stratified (Fig. 14B, Fig. 23). At some sites this is most likely due to syn- and/or post-sedimentary bioturbation as e.g. roots or traces thereof can be seen penetrating deep into the dunes and laminations being better preserved with increasing depth. However, e.g. at Brattforsheden this is not so obvious. The vaguely stratified sands could be due other dominating depositional processes (e.g. grain fall, grain flow, cf. Hunter 1977) or conditions (e.g. deposition together with snow, cf. Ahlbrandt & Andrews 1978).

Extent and relevance of aeolian deposits

The area covered by (mapped) aeolian deposits in Sweden is 379 km^2 according to the data extracted from SGU's databases (cf. Fig. 1), which corresponds to 0.09% of Sweden's land area (407310 km^2; SCB 2016). Individual inland dune fields in Sweden are in global comparison also small. As mentioned above, Bonäsheden is with its 15.5 km^2 the largest continuous dune field in Sweden (Bergqvist 1981; Bernhardson & Alexanderson submitted) and the other dune fields are even smaller.

Aeolian deposits are thus a very small landscape element but their distinctiveness makes them conspicuous and they are commonly appreciated for their 'special nature', e.g. as recreational areas. This is reflected by that the Mora field, including Bonäsheden, was nominated as a Geological heritage site in 2014 (SGU 2014) and before that recommended for designation as an area of national interest, together with five other dune fields (Bergqvist 1981). Other areas with aeolian deposits have also been partly or wholly protected as natural reserves (e.g. Brattforsheden, Ängelholms strandskog) or even national parks (Store Mosse). However, this is a fairly recent feature; for a long time fields of aeolian sand were mostly considered a nuisance (cf. Ljungberg 2004).

These sandy deposits are also the home for various living organisms, some of which are completely dependent on access to open sand patches, such as the sand lizard, some Carabidae beetles and blue hair grass (Berglind 2000; Ljungberg 2004; Ödman 2013). The aeolian landscape element is thus also of importance from the perspective of biodiversity, and an understanding of its formation, as well as its subsequent use, is key to informed management and preservation of such areas (cf. Ödman 2013).

Most occurrences of aeolian sediments in south-central Sweden are closely connected to extensive sandy deposits that provided the source of the material (Högbom 1923). Dunes and larger coversand deposits are thus mainly found at glacifluvial deltas, on the beds of former glacial lakes and on raised beach ridges. This is similar to other previously glaciated areas (e.g. Högbom 1923; Muhs & Wolfe 1999; Halfen *et al.* in press) and suggests that sediment supply is the key factor for dune formation here.

The temporal extent of aeolian deposition is discussed above.

Future research

Most of our data are from Early Holocene inland dunes, with a particular emphasis on some of the larger dune fields in central Sweden. A smaller part of the dataset comes from older or younger coversands, isolated dunes, sparse dune fields or coastal dunes. This focus was a deliberate choice in the project, to at least partly limit the number of variables affecting the records we studied. However, these other features may contain a slightly different record than the large inland dune fields, and may, with the exception of the coastal dunes, also be less well inventoried since they are not as prominent. For example, coversands are found in more areas than dunes and could thus provide a geographically broader, but temporally shorter archive. Future studies into these other archives would thus be interesting to get a broader perspective on the aeolian activity.

Dunes and similar deposits are episodical records that commonly record few events, with a bias towards the youngest event (Halfen *et al.* 2012; in press). More continuous records of sand drift can be retrieved from interdune areas, lake sediments or bogs, where the flux of wind-blown sediment into basins can be reconstructed (Björck & Clemmensen 2004; Sjögren 2009). This has been done in some areas in Sweden, e.g. in Halland (Björck & Clemmensen 2004; de Jong *et al.* 2006), and was planned to be carried out also during this project at selected basins close to our key areas, e.g. the Siljan area and Brattforsheden. However, for various reasons it was not done, and should be done in future aeolian research. We do nevertheless have access to existing records from other researchers for some areas, e.g. Store Mosse (Kylander *et al.* 2013). Although both dunes and wind-blown sand in basins record aeolian activity, they do not necessarily record the same things and can be used to supplement each other to e.g. resolve seasonality, as was recently shown by Nielsen *et al.* (2016) for a coastal dune field and lake in NW Norway.

More continuous records of climatic and environmental change from e.g. lake sediments would also be useful to better understand the likely complex causes of sand drift during the Mid- and Late-Holocene, particularly when human impact becomes significant. For the youngest events, historical records are also available, as shown in Kalińska-Nartiša *et al.* (in press). We find the Mid-Holocene event particularly interesting as an apparent regional event.

The studies of coastal dunes that we did during the last year of the project (Kristianstad, Ängelholm) potentially leads into other, more applied aspects of aeolian research. Due to ongoing climatic changes it is expected that coastal areas are going to experience adverse effects in the near future (IPCC 2014), e.g. increased coastal erosion and flooding. Skåne is the area in Sweden that is likely to suffer most from the changing coastal conditions. Here, the land is no longer being uplifted and much of the coastline is made up of loose sediments, making it more susceptible to e.g. an increased sea level (Malmberg Persson *et al.* 2014). Today, 3000 houses are subject to risk of coastal flooding and in year 2100, around 23,000 houses will be at risk, assuming a rise of mean sea level by 1 m (Ehrnstén *et al.* 2014).

A better understanding of coastal systems is therefore critical. For example, sustainable planning of coastal areas requires both short- and long-term predictions of beach-dune system evolution and a good grasp of foredune dynamics, since dunes commonly serve as flood defence for low-lying hinterlands and as a sediment reserve for the beach. Modelling, such as that carried out by our colleagues at LTH (Larson *et al.* submitted) is one way to make predictions and improve understanding, but a long-term perspective requires other kinds of data that involve geological expertise. By using techniques tested during the pilot studies within this project (e.g. quartz grain analyses, OSL dating, sediment source tracing) it would be possible to address timing and rates of coastal development, progradation or erosion, identify past storm events and sediment sources.

The work carried out in this project has also shown the great potential of LiDAR data for geomorphological mapping. There is no doubt that this data set will lead to many new discoveries and improved knowledge of the Quaternary history of Sweden. The results of OSL dating have also pointed us in directions for future methodological development, such as sediment tracing and dating problematic samples.

Conclusions

In a global perspective the Swedish aeolian deposits are very small; they cover less than 0.1% of the country's land area and largest dune field in Sweden is only ~15.5 km². Nevertheless, they contain an interesting palaoeenvironmental archive, which so far has been largely unexplored despite that the deposits have to a large extent been mapped. To explore this archive, we have in this project investigated dune fields, single dunes and coversands at 70 sites in south-central Sweden by geomorphological, sedimentological, geophysical and geochronological techniques as well as by literature and map studies.

Our results provide the first numerical ages of aeolian activity in several of these areas and we are thereby able to establish a chronological framework of sand drift in south-central Sweden. The results confirm the hypothesis of previous investigators (e.g. Högbom 1923; Hörner 1927; Bergqvist 1981) that the bulk of the aeolian sediments were deposited shortly after the last deglaciation, ranging in age from c. 15.2 ka in Skåne to c. 10.5 ka in Dalarna. In the Värmland-Dalarna dune fields, which are the best developed in Sweden, dunes appear to have continued to form for 1500-2000 years following deglaciation. Thus, they were still active after vegetation had become established in the area. Detailed geomorphological mapping based on the excellent LiDAR data (Lantmäteriet 2015) shows that – at least in one dune field (Bonäsheden, Dalarna) – there is a change in dune orientation, type and size over time during this early period of dune formation. This likely reflects changes in wind pattern and/or vegetation cover as the ice sheet retreated and climate ameliorated.

Dunes formed just after deglaciation have not been significantly reworked during the Holocene and their geomorphology largely still reflects the original, generally transverse dune type. This allows reconstruction of palaeowinds, and the dune orientation (~NE-SW) in at least the northern part of our study area, indicates formation mainly by northwesterly winds, also in agreement with most previous studies of these sites (e.g. Högbom 1923).

The largest dune fields or groups of dunes are found at glacifluvial deltas, on the beds of former glacial lakes or along raised beaches, suggesting that sediment supply is a key controlling factor for dune-field location in Sweden. At the time of deglaciation, when most of these dunes formed, there was also good sediment availability since the sparse vegetation did not bind the sand significantly, and the strong katabatic winds provided large transport capacity. Later episodes of sand drift in south-central Sweden have been limited in time and space and mainly resulted in coversand deposition, with dune formation only at a few sites. This limited extent is most likely a result of insignificant new sediment supply, reduced sediment availability because of rich vegetation and a lower transport capacity due to less strong winds.

Taking the (partly still preliminary) ages of the Mid- and Late Holocene events at face value, they seem to be part of regional periods of increased storminess in northern Europe (e.g. Clemmensen *et al.* 2009; Sorrel *et al.* 2012). This suggests a non-local cause, e.g. changing circulation patterns in the North Atlantic region that influenced climate, and which influenced mainly transport capacity. For some of the young deposits, a local, human impact cause affecting sediment availability is, however, more likely (e.g. forest destruction, or changed agricultural practice), and for the coastal dunes, sea-level change plays a significant role. Palaeowind directions determined from the younger dunes vary from site to site.

The sediment forming the dunes and coversand is in almost all studied sites dominated by well-sorted fine-medium sand, while sedimentary structures vary geographically and stratigraphically, indicating a range of depositional and post-depositional processes. For example, in the Dalarna dune fields, the sand is distinctly laminated, a result of wind-ripple migration on both windward- and lee sides of the dunes. Syn- and post-depositional bioturbation has disturbed the structures to varying degrees at most sites and in some areas, primary structures have been largely destroyed, at least in the upper 0.5-1.5 m.

Surface and shape characteristics of quartz grains within dune sand show relatively few traces of aeolian reworking and instead retain the characteristics of the depositional environment of the source sediment, e.g. glacifluvial sand. This shows that the aeolian transport was limited in time and/or space during dune formation. Younger coversand, on the other hand, has a larger proportion of 'aeolian grains' as a result of more extensive reworking by aeolian processes.

Acknowledgements

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App. 1. Fieldwork

List of fieldwork carried out within the project, including participants

Time	Area	Participants	Purpose
October 2013	Dalarna	MB, HA	Sampling and survey of Bonäsheden
May 2014	Dalarna, Värmland	MB, HA, LJ	GPR investigation and supplementary sampling of Brattforsheden and Bonäsheden, survey of Lerbäcksmon
May 2014	Småland	MB	Survey and very limited sampling of Store Mosse and adjacent areas
September 2014	Skåne	EKN, HA	Sampling and survey of Åhus and Vittskövle
February 2015	Småland	MB, HA, SF, EKN	Sampling and survey of sites at Store mosse
May 2015	Väster- och Östergötland, Närke, Värmland	HA, SAA	Survey and sampling of several sites in this area
October 2015	Dalarna	MB, SF, HA	Supplementary sampling of Bonäsheden, survey of Haftaheden
December 2015	Skåne	HA, CF	Profiling, documentation and sampling of foredune at Skälderviken/Ängelholm
May 2016	Dalarna	MB, MEA, LJ	GPR investigation and supplementary sampling of Haftaheden
May 2016	Skåne	MBj, CF	Profiling and sampling of dunes at Skälderviken/Ängelholm

Participants

CF	Caroline Fredriksson
EKN	Edyta Kalińska-Nartiša
HA	Helena Alexanderson
LJ	Leif Jakobsen
MB	Martin Bernhardson
MBj	Mark Björnfors
MEA	Mohammed El Ali
SAA	Sven-Allan Alexanderson

App. 2. Investigated sites

Table with GPS-coordinates for sites and info on type of site and investigations/samples done there

Region	Area	Site	Latitude (°N)	Longitude (°E)	Deposit type	Sediment exposure	Logging	GPR	OSL	C14	Grain-size analyses	Grain shape & surface	Microtextures (SEM)	Principal investigator	Number of OSL samples	Number of C14	Comment
Dalarna	Bonäsheden	Bonäs 10	61.0662	14.4583	dune	none (auger)	x		x					MB	1		
Dalarna	Bonäsheden	Bonäs 11	61.0654	14.4615	dune	hand-dug hole	x		x					MB	1		
Dalarna	Bonäsheden	Bonäs 12	61.0793	14.4753	dune	none (auger)			x					MB	2		
Dalarna	Bonäsheden	Bonäs 1a	61.0739	14.4820	dune	sand pit	x	x	x					MB	2		
Dalarna	Bonäsheden	Bonäs 1b	61.0732	14.4825	dune	sand pit	x	x	x					MB	2		
Dalarna	Bonäsheden	Bonäs 2	61.0484	14.4705	dune	former sand pit	x	x	x					MB	2		
Dalarna	Bonäsheden	Bonäs 3	61.1002	14.4700	dune	active sand pit	x	x	x			x		MB	8		
Dalarna	Bonäsheden	Bonäs 4	61.0946	14.4784	dune	hand-dug hole	x	x	x	x				MB	2	2	
Dalarna	Bonäsheden	Bonäs 5	61.0811	14.4481	dune	hand-dug hole	x		x	x				MB	2	1	
Dalarna	Bonäsheden	Bonäs 6	61.0743	14.4477	dune	hand-dug hole	x	x	x					MB	3		
Dalarna	Bonäsheden	Bonäs 7	61.1030	14.4459	dune	none (auger)	x	x	x					MB			
Dalarna	Bonäsheden	Bonäs 8	61.0634	14.4766	dune	hand-dug hole	x		x					MB	2		
Dalarna	Bonäsheden	Bonäs 9	61.0626	14.4685	dune	none (auger)	x		x					MB	1		
Dalarna	Haftaheden	Hafa 1	60.4728	13.9228	dune	sand pit	x	x	x	x				MB	3	1	
Dalarna	Haftaheden	Hafa 2A	60.4575	13.9051	dune	road cut	x	x	x					MB	2		
Dalarna	Haftaheden	Hafa 2B	60.4576	13.9049	dune	hand-dug hole	x	x	x					MB	1		
Dalarna	Haftaheden	Hafa 3	60.4486	13.8885	dune	road cut	x	x	x					MB	2		
Dalarna	Haftaheden	Hafa 4	60.4405	13.9451	dune	road cut	x	x	x					MB	2		
Dalarna	Haftaheden	Hafa 5	60.4519	13.8899	dune	road cut	x	x	x					MB	2		
Dalarna	Haftaheden	Hafa 6	60.4566	13.8873	esker	road cut	x	x	x					MB	5		
Dalarna	Haftaheden	Hafa 7	60.4418	13.9236	esker	none		x						MB			
Dalarna	Skattungheden	Orsa 1	61.1712	14.6940	dune/interdune	small cut	x		x		x			MB	3		
Dalarna	Skattungheden	Orsa 2	61.1722	14.6851	dune	road cut	x		x		x			MB	4		
Dalarna	Skattungheden	Orsa 3	61.1762	14.6906	dune	road cut	x		x		x			MB	4		
Dalarna	Skattungheden	Orsa 4	61.1849	14.7295	delta	sand pit	x		x		x			MB	2		
Dalarna	Skattungheden	Orsa 5	61.1741	14.6903	dune	hand-dug hole	x		x					MB	3		
Dalarna	Skattungheden	Orsa 6	61.2025	14.8536	esker	road cut			x					MB	1		
Närke	Kumla	Alltorp	59.1069	15.5511	dune	small cut	x		x					HA	1		
Närke	Kumla	Bodatorp	59.1086	15.5432	dune	hand-dug hole	x		x					HA	1		
Närke	Kumla	Kulan	59.1109	15.5404	dune	small cut	x		x					HA	3		
Skåne	Kristianstad plain	Vitskövle	55.8470	14.1500	beach ridges with dunes	hand-dug hole	x		x	x	x	x	x	EKN	2	1	see Kalinska-Nartisa et al. (2016)
Skåne	Kristianstad plain	Åhus 1	55.8967	14.2727	coastal dune	hand-dug hole	x		x		x	x	x	EKN	2		see Kalinska-Nartisa et al. (2016)
Skåne	Kristianstad plain	Åhus 2	55.8969	14.2725	coastal dune	hand-dug hole	x		x		x	x	x	EKN	4		see Kalinska-Nartisa et al. (2016)
Skåne	Kristianstad plain	Åhus 3	55.8968	14.2619	inland dune	hand-dug hole	x		x		x	x	x	EKN	2		see Kalinska-Nartisa et al. (2016)
Skåne	Vomb basin	Blentarp	55.5889	13.2369	cover sand	active sand pit	x		x	x	x			RS	12	2	see Shrestha (2013)
Skåne	Vomb basin	Lake Vomb	55.6800	13.6000	lake sediment	core	x		x	x				KL	3		C14 in Ljung et al. (2014)
Skåne	Ängelholm	Blocklinjen	56.2496	12.8264	active foredune	wave-eroded cut	x		x					HA	3		see Björnfors (2016)
Skåne	Ängelholm	Profil J	56.2571	12.8322	active foredune	core, hand-dug	x		x		x			HA	2		see Björnfors (2016)
Skåne	Ängelholm	Profil L	56.2546	12.8319	dunes	hand-dug hole					x			MBj			see Björnfors (2016)
Skåne	Ängelholm	Profil N	56.2457	12.8229	dunes	hand-dug hole					x			MBj			see Björnfors (2016)
Skåne	Ängelholm	Profil O	56.2376	12.8153	active foredune	wave-eroded cut	x		x		x			HA	4		
Småland	Store Mosse	Sandliden	57.2577	13.8356	dune	sand pit	x		x		x			HA	5		
Småland	Store Mosse	Bredaryd	57.1568	13.7397	dune	road cut	x		x		x			MB	2		

Region	Area	Site	Latitude (°N)	Longitude (°E)	Deposit type	Sediment exposure	Logging	GPR	OSL	C14	Grain-size analyses	Grain shape & surface	Microtextures (SEM)	Principal investigator	Number of OSL samples	Number of C14	Comment
Värmland	Brattforsheden	Fallet	59.7337	13.8401	dune	none		x						HA			
Värmland	Brattforsheden	Gräshöjden 1	59.6078	13.9536	dune	road cut	x	x				x		HA			cf Alexanderson & Fabel (2015)
Värmland	Brattforsheden	Gräshöjden 2	59.6083	13.9531	dune	none	x	x						HA			
Värmland	Brattforsheden	Långa manen	59.6172	13.9636	dune	none	x	x						HA			
Värmland	Brattforsheden	Långbromana 1	59.7207	13.8678	dune with blow-out	hand-dug	x	x	x	x				HA	3	2	
Värmland	Brattforsheden	Långbromana 2	59.7209	13.8611	dune	hand-dug	x	x	x					HA	3		
Värmland	Brattforsheden	Nabbmanen	59.7176	13.8739	dune	road cut	x	x				x		HA			cf Alexanderson & Fabel (2015)
Värmland	Sörmon	Sörmon 1	59.3885	13.3645	beach ridges with dunes	former sand pit	x		x					HA	4		
Värmland	Sörmon	Sörmon 2	59.3899	13.3670	beach ridges with dunes	former sand pit	x		x					HA	1		
Värmland	Törnemon	Törnemon	59.3868	13.2509	dune	sand pit	x		x					HA	3		
Västergötland	Skara	Bäckåsen	58.3729	13.3245	dune	small sand pit	x		x					HA	2		
Västergötland	Skara	Karstorp	58.3408	13.2884	dune	sand pit	x		x					HA	3		
Västergötland	Skara	Nyängen	58.4196	13.3422	dune	old household pit	x		x					HA	2		
Västergötland	Skara	Skogalund	58.4186	13.3427	dune	small road cut	x		x					HA	3		
Västergötland	Skövde	Laggartorp	58.4688	14.0842	dune	old household pit	x		x					HA	2		
Västergötland	Skövde	Skövde flygplats	58.4605	13.9629	mound	hand-dug hole	x		x					HA	2		
Västergötland	Skövde	Stenebacken	58.4737	14.1991	dune	old household pit	x		x					HA	1		
Västergötland	Skövde	Valstaberg	58.4572	14.1961	dune	small road cut	x		x					HA	2		
Västergötland	Tidaholm	Kobonäs	58.2231	13.9548	dune	hand-dug hole	x		x					HA	2		
Västergötland	Tidaholm	Munkaledet 1	58.2584	13.8286	dune	hand-dug hole	x		x					HA	3		
Västergötland	Tidaholm	Munkaledet 2	58.2568	13.8380	dune	hand-dug hole	x		x					HA	2		
Östergötland	Lerbäck	Fixan	58.9354	15.0372	dune	none (auger)	x		x					HA	1		
Östergötland	Lerbäck	Lerbäcksmon	58.9402	15.0337	dune	road cut	x		x					HA	3		
Östergötland	Lerbäck	Stora Björnfall	58.8468	15.1787	dune	abandoned sand pit	x		x					HA	2		
Östergötland	Lerbäck	Vissbodamon	59.0127	15.0379	dune	abandoned sand pit	x		x					HA	2		
Östergötland	Mjölby	Mjölbyfältet	58.3613	15.1202	dune	none (auger)	x		x					HA	1		
Östergötland	Mjölby	Öjebrotorpen	58.3620	15.1860	dune	hand-dug hole	x		x					HA	2		

Total no of samples 152   9

Principal investigators

EKN	Edyta Kalińska-Nartiša
HA	Helena Alexanderson
KL	Karl Ljung
MB	Martin Bernhardson
MBj	Mark Björnfors
RS	Rajendra Shrestha

App. 3. Publications and presentations

Peer-reviewed papers

1. Bernhardson M & Alexanderson H. submitted. Early Holocene dune field development in Dalarna, Central Sweden: a geomorphological and geophysical case study. *Earth Surface Processes and Landforms*.

2. Alexanderson H & Bernhardson M. in press. OSL dating and luminescence characteristics of aeolian deposits and their source material, Dalarna, central Sweden. *Boreas*. doi: 10.1111/bor.12197

3. Kalińska-Nartiša E, Alexanderson H & Nartišs M. in press. A luminescence chronology of aeolian-coastal events on the Kristianstad plain, SE Sweden. *The Holocene*. doi: 10.1177/0959683616652707

Manuscripts

4. Kalińska-Nartiša E, Alexanderson H, Nartišs M, Stevic M & Kaiser K. Sedimentary features and transportation pathways of the Holocene and Lateglacial sediments in the Kristianstad plain, SE Sweden.

5. Bernhardson M. The dune field at Haftaheden, central Sweden.

Conference presentations

1. Kalińska-Nartiša E, Alexanderson H & Nartišs M. 2016: When did the coast form? *Climate change adaptation in the coastal zone*, Malmö, Sweden. 5-6 April 2016.

2. Nartišs M, Kalińska-Nartiša E & Alexanderson H. 2016: Kāpu veidošanās laiks Krišanstades līdzenumā, Zviedrijā. *Latvian University, 74th Scientific conference: Geography, geology and environmental science*, Riga, Latvia. 25 January-18 March 2016.

3. Alexanderson H. 2016: Finding a good place to date. *32nd Nordic Geological Winter Meeting*, Helsinki, Finland. 13-15 January 2016.

4. Bernhardson M & Alexanderson H. 2016: The aeolian dunes of Bonäsheden, central Sweden: a geomorphological, geophysical and geochronological case study. *32nd Nordic Geological Winter Meeting*, Helsinki, Finland. 13-15 January 2016.

5. Bernhardson M & Alexanderson H. 2014. Aeolian deposits from central Sweden: Adding another piece to the palaeoenvironmental puzzle. *14th International Conference on Luminescence and Electron Spin Resonance Dating (LED2014)*, Montreal, Canada. 7-11 July 2014. Poster.

6. Alexanderson H, Bernhardson M, Henriksen M, Jakobsen LV & Shrestha R. 2014: Inland dunes and cover sand in southern Sweden and Norway – evidence of late glacial and historical aeolian activity. *31st Nordic Geological Winter Meeting*, Lund, Sweden. 8-10 January 2014. Talk.

7. Bernhardson M & Alexanderson H. 2014: Mapping aeolian landforms: preliminary results from south-central Sweden. *31st Nordic Geological Winter Meeting*, Lund, Sweden. 8-10 January 2014. Poster.

8. Ljung K, Alexanderson H, Ning W & Broström A. 2014: Reconstruction of land-use change and erosion within the catchment of Lake Vomb in southern Sweden. *31st Nordic Geological Winter Meeting*, Lund, Sweden. 8-10 January 2014. Poster.

9. Alexanderson H. 2013: The Lund Luminescence Laboratory – facilities and ongoing projects. *UK Luminescence & ESR meeting 2013*, St Andrews, Scotland. 28-30 August 2013. Poster.

10. Alexanderson H, Shrestha R, Bernhardson M & Florén S. 2013: OSL dating of inland dunes and cover sand in southern Sweden – evidence of late glacial and historic aeolian activity. *UK Luminescence & ESR meeting 2013*, St Andrews, Scotland. 28-30 August 2013. Poster.

Excursion / excursion guide

1. Alexanderson H & Bernhardson M. 2015: Stop 2.1 Händene dune field. In: Johnson MD (ed.): *The 2nd annual NORDQUA field trip Deglacial history and geomorphic development of the area between Vänern and Vättern: Younger Dryas moraines, the Baltic Ice Lake drainage and the dynamic Vättern lobe*. p. 35-37.

Student theses

1. Bernhardson M. in prep.: *Aeolian dunes of central Sweden/Scandinavia*. PhD thesis, Department of

Geology, Lund University, Lund.

2. El Ali M. in prep.: *Flygsanddyners inre uppbyggnad - georadarundersökning*. BSc thesis, Department of Geology, Lund University, Lund.

3. Björnfors M. 2016: *Kusterosion och äldre kustdyners morfologi i Skälderviken*. BSc thesis 478, Department of Geology, Lund University, Lund. URL: http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8883011&fileOId=8883626

4. Stevic M. 2015: *Identification and environmental interpretation of microtextures on quartz grains from aeolian sediments : Brattforsheden and Vittskövle, Sweden*. BSc thesis 446. Department of Geology, Lund University, Lund. URL: http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=5468853&fileOId=5468922

5. Olsenius B. 2014: *Vinderosion, sanddrift och markanvändning på Kristianstadslätten*. BSc thesis 409. Department of Geology, Lund University, Lund. URL: http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=4465965&fileOId=4465971

6. Shrestha R. 2013: *Optically stimulated luminescence (OSL) dating of aeolian sediments of Skåne, south Sweden*. MSc thesis 333. Department of Geology, Lund University, Lund. URL: http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=3633520&fileOId=3633526

Other presentations including popular science

1. Bernhardson M. 2015: Aeolian dunes in Sweden: adding another piece to the palaeoenvironmental puzzle. *ClimBEco Graduate Research School Summer Meeting*, Falsterbo, Sweden. 26-27th August 2015

2. Bernhardson M. 2015: Aeolian dunes in Sweden: adding another piece to the palaeoenvironmental puzzle. *Geological Survey of Sweden (SGU) seminar,* Uppsala, Sweden. 28th April 2015

3. Bernhardson M. 2014: Flygsand – ett outforskat klimatarkiv. *NMT-dagarna för gymnasieelever och lärare,* Lund, Sweden. 10-14th March 2014

Lundqua Report

24. Lagerlund, E. et al., 1983: The deglaciation pattern and dynamics in South Sweden : a preliminary report.

25. Gaillard, M-J., 1984: A palaeo-hydrological study of Krageholmssjön (Scania, South Sweden) : regional vegetation history and water-level changes.

26. Digerfeld, G. (ed.), 1987: IGCP 158 : paleohydrological changes in the temperate zone in the last 15000 years : symposium at Höör, Sweden, 18-26 May 1987 : excursion guide.

27. Gaillard, M-J. (ed.), 1987: IGCP 158 : paleohydrological changes in the temperate zone in the last 15000 years : symposium at Höör, Sweden, 18-26 May 1987 : abstracts of lectures and posters.

28. Kolstrup, E. & Håkansson, Håkansson, H., 1987: Early and middle holocene developments in Herrestads Mosse (Scania, South Sweden). Part 1, Diatom analysis and vegetational development.

29. Harrison, Sandy P., 1988: Lake-level records from Canada and the eastern U.S.A.

30. Lemdahl, G., 1988: Late Weichselian insect assemblages from the Kullen peninsula, South Sweden : palaeo-environmental interpretations.

31. Göransson, H., 1991: Vegetation and man around Lake Bjärsjöholmssjön during prehistoric time.

32. Lagerlund, E. (ed.), 1990: Methods and problems of till-stratigraphy - INQUA -88 [in Lund, Sweden 25-30 September 1988] : proceedings : symposium and field trip in southern Sweden 25-30 September 1988.

33. Möller, P., Hjort, C. & Ingólfsson, O. (eds.), 1991: The last interglacial-glacial cycle : preliminary report on the PONAM fieldwork in Jameson Land and Scoresby Sund, East Greenland : proceedings of the Ponam workshop in Skanör, Sweden 23-26.4 1991.

34. Bartholin, T. et al. (eds.), 1992: Tree rings and environment : proceedings of the International Dendrochronological Symposium, Ystad, South Sweden, 3-9 September 1990.

35. Möller, P. et al. (eds.), 1992: Weichselian and Holocene glacial and marine history of East Svalbard : preliminary report on the PONAM fieldwork in 1991 : proceedings of the PONAM workshop in Asker, Norway 27-29.4 1992.

36. Regnell, M., 1998: Archaeobotanical finds from the Stone Age of the Nordic countries : a catalogue of plant remains from archaeological contexts.

37. Sandgren, P. (ed.), 2000: Environ-mental changes in Fennoscandia during the Late Quaternary.

38. Linderson, H., 2003: A comparison between tree-ring widths of recent Scots pine (*Pinus sylvestris*) and Norway spruce (Picea abies) stands and meteorological data from two areas in Sweden : inferences for the use of tree-ring width as climate indicator.

39. Holmqvist, B.H., 2005: Classification of large pollen datasets using neural networks with application to mapping and modelling pollen data.

40. Möller, P. 2010: Sub-till sediments on the Småland peneplain : their age, and implications for south-Swedish glacial stratigraphy and glacial dynamics.

41. Möller, P., Barnekow, L. & Sandgren, P., 2011: Rekonstruktion av paleomiljön för området kring stenåldersboplatserna vid Aareavaara, Norrbotten : jägarboplatser vid randen av en inlandsis?!

42. Alexanderson, H., Bernhardson, M. & Kalińska-Nartiša, E. 2016: Aeolian activity in Sweden: an unexplored environmental archive.

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