A revised chronology for aeolian activity in subarctic Fennoscandia during the Holocene

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Received 23 June 1998; revised manuscript accepted 2 October 1998

A HOLOCENE RESEARCH PAPER

Abstract: Detailed sedimentological studies and parallel sampling for ^{14}C and infra-red stimulated luminescence age assays were undertaken at six sites lying beyond and below the tree-line with the objective of establishing the historical development of aeolian landforms in Lapland. The main issues were: (a) the timing of dune activity and processes of stabilization; (b) the specific processes responsible for the past and contemporary activity. New data indicate that many of the primary dunes were active for several millennia after deglaciation. Diachronous stabilization at both local and regional scales appears likely. Initial stabilization occurred in local interdune areas and where regional dune fields were colonized by pine (generally before 7 ka). Local large dunes and some regional dunefields only became stable around 4.3 ka, when the regional groundwater table rose and late pine colonization was possible. The latest episode of aeolian activity dates from AD 1100–1650 across the area. A unique deflation triggering factor was not identifiable, suggesting that several agents acted in combination. Climate-vegetational parameters, especially the 'Little Ice Age' event, together with reindeer trampling, appear responsible for the continuing aeolian activity at the tundra sites. At the margin of the pine forest zone, forest fires may be the cause of aeolian reactivation.

Key words: Aeolian activity, charcoal horizons, IRSL dating, Holocene, luminescence dating, climatic change, reindeer, Lapland.

Introduction

Most inland dunes in northern Fennoscandia are currently anchored and vegetated with dwarf shrubs (*Arctostaphylos uva-ursi*, *Betula nana*, *Calluna vulgaris*, *Empetrum nigrum* subsp. *hermaphroditum*, *Vaccinium vitis-idaea*, etc.), mountain birch (*Betula pubescens* subsp. tortuosa) or Scots pine forest (*Pinus sylvestris*). Active parabolic dunes *sensu stricto* are only found in a few locations (Käyhkö *et al.*, 1996). In contrast, active blowouts occupying the crestal zones of the former active dunes are quite common beyond the pine forest zone. The redeposited rims of sand at the margin of active aeolian surfaces often reveal stratigraphic evidence of episodic instability in the form of stacked buried podsol soils associated with charcoal in the A_0 horizons. The wide distribution of dunes indicates an earlier period when the environment was more favourable for dune development.

Since aeolian landforms are known to be sensitive indicators of environmental changes (e.g., Filion 1984; Pye *et al.*, 1995; Wolfe *et al.*, 1995), the temporal framework of dune response to Holocene environmental changes potentially provides an enhanced understanding of former and future aeolian activity in cold environments. Key factors in the study approach are a wide areal coverage, contrasting vegetation zones, and a critical evaluation of the sedimentological evidence. The main issues discussed are: (a) the timing of dune activity and stabilization process; (b) the processes responsible for the past and contemporary activity.

Study area

The limits of the study area were determined by the coverage provided by 11 Landsat TM quarter images that were used to map

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0959-6836(99)HL302RP

the aeolian features (Figure 1) (Käyhkö *et al.*, 1996). It lies between latitudes 68° and 70°N in northern Lapland. The surficial geology of the area reflects the deglaciation of the Fennoscandian ice sheet, which took place approximately 12 000–8500 BP (Sollid *et al.*, 1973; Ignatius *et al.*, 1980), revealing spreads of glaciogenic sediments. These deposits acted as source areas for aeolian sediment transport with most dunes developing adjacent to eskers and glaciolacustrine areas.

The mean annual temperature varies from +1°C in the south to –2°C in the northwest, and the northern part of the area is affected by sporadic permafrost (Helminen, 1987). Cyclonic activity induces variable wind directions, with some prevalence of south-westerlies in the south and northwesterlies in the north (FMI, 1991). Precipitation follows a gradient from more humid near the coast to drier inland. Typically, the annual precipitation is 500–550 mm, approximately half of which falls as snow. The annual potential evaporation varies between 100 and 225 mm. Snow lies for 200–220 days per year, and the average maximum snow depth is 50–60 cm (Solantie, 1987).

Vegetationally, the area is part of the northern boreal zone (Ahti *et al.*, 1968; Oksanen and Virtanen, 1995). The duration of the growing season varies between 95 and 130 days. Polar tree-lines for both Scots pine and Norway spruce (*Picea abies*) cross the area. Further north, and at higher elevations in the hills, trees are limited to mountain birch, which forms a sparse park-like scrub with a flourishing lichen ground layer. However, due to intensive reindeer herding, many areas are currently almost devoid of lichens such as *Cladina stellaris* and *C. mitis,* which form important winter forage for these animals. *Cladina* species have been replaced by dwarf shrubs and other lichen species (Käyhkö and Pellikka, 1994). Disturbance of the ground vegetation cover by reindeer has been proposed as a possible reason for wind erosion in the area (cf. Kotilainen, 1991; Käyhkö, 1994; Seppälä, 1995; Tikkanen and Heikkinen, 1995).

Earlier studies

Previously published dune studies from the area are of two kinds. First, dune inventories, including Seppälä (1972) and Bergqvist (1981) for Sweden, Klemsdal (1969) for Norway, and Tikkanen and Heikkinen (1995) for Finland. Käyhkö *et al.*, (1996) have recently mapped aeolian activity in northern Fennoscandia across national borders using Landsat TM data. Second, stratigraphical studies of aeolian deposits, including Bergqvist and Lindström (1971) in central Sweden, and Aartolahti (1976), Seppälä (1981; 1995), Kotilainen (1991), Vliet-Lanoë *et al.* (1993) and Tikkanen and Heikkinen (1995) in Finland. Figure 2 presents a compilation of published data related to Holocene active aeolian phases in northern Finland.

Until 1991, the only radiometric date with which the initial post-deglaciation dunebuilding phase was correlated was Seppälä's (1971) uncalibrated age of 7160 ± 200 BP (Hel-31), obtained from a buried charcoal horizon associated with a mature podsol at Kiellajoki, Finnish Lapland. Seppälä concluded that aeolian activity had ceased rapidly after deglaciation due to vegetation succession. Since then, luminescence age estimates from other dunefields have indicated that the end of the initial dunebuilding episode may be some 1000 years later, at around 7 ka, suggesting regional variation in aeolian activity. Subsequent assays have blurred the simple picture that was presented in the early papers. It is likely that as more geochronological data become available the pattern will become more complicated. All of the previous stratigraphic studies have been undertaken in the vicinity of the present pine tree-line with the possible limitation that the regional pattern in aeolian activity might not be decipherable. In this study, a conscious attempt was made to seek active aeolian areas in the pure birch woodland and treeless tundra as well as the pine forests.

Methods

From the 63 localities known to be affected by deflation (Käyhkö *et al.*, 1996) in the study area, six were selected for geochronological investigations reported in this paper (Figure 1; Table 1). It was hoped that the wide areal distribution of these sites would help identify those environmental factors which control recurrent aeolian activity. The blowout rim deposits were excavated by hand, and, in order to elucidate the timing of the processes which have created the deflation features, selected sediment units were sampled for dating and particle-size analysis. Some aspects of the dating of aeolian deposits are discussed in the following.

Radiocarbon dating

The traditional method for interpreting aeolian history is radiocarbon dating of buried soil horizons. Any ^{14}C age estimate of a surface soil provides a relative age, often called the *apparent mean residence time* (AMRT). The absolute (true) age of a surface soil, defined as the period of time since the commencement of humus formation in the regolith, will always be older than the

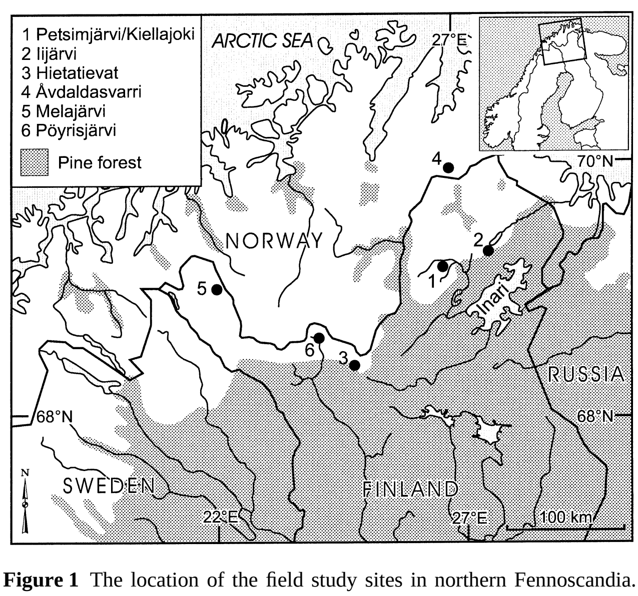

Figure 1 The location of the field study sites in northern Fennoscandia.

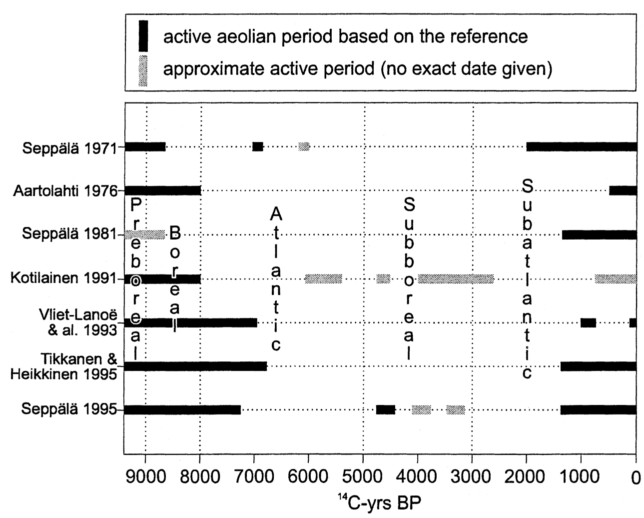

Figure 2 A compilation of previously published evidence for the timing of aeolian episodes during the Holocene in Finnish Lapland.

Table 1 The study sites in northern Fennoscandia

Site name	Location*	Sediment type	Vegetation
Petsimjärvi-Kiellajoki	3494900, 7688100	aeolian	birch-pine
	3491200, 7693600	glaciofluvial	birch-pine
Iijärvi	3524900, 7699500	aeolian	birch-pine
Hietatievat	3406250, 7599950	aeolian	birch-pine
Åvdaldasvarri	69°58′N, 27°00′E	aeolian	birch
Melajärvi	3302000, 7659000	aeolian	birch
Pöyrisjärvi	3372200, 7626700	aeolian	tundra

* Coordinates according to the Finnish national grid (27° UTM, 3500 km false easting), except in Norway (lat/long WGS-84).

AMRT of the uncontaminated soil organic matter within it (Geyh *et al*., 1983; Matthews, 1984). A ^{14}C age estimate from a soil is therefore a *minimum* estimate of the absolute soil age, whatever fractionation technique may be used (Gilet-Blein *et al*., 1980). Consequently, a ^{14}C age estimate from a buried soil provides a *maximum* estimate of the period of time for which the soil has been buried. The most common organic fractions analysed are NaOH-soluble (humic acid), NaOH-insoluble (residue), or the total fraction. As demonstrated by Martin and Johnson (1995), any correlation between radiocarbon age estimates obtained from different organic fractions – and also from different laboratories – should be made with caution. Another factor to be considered with respect to dating buried soil organic matter is the possible age–depth gradient within the soil horizon (cf. Matthews and Dresser, 1983). It has been suggested that the date of burial of a palaeosol is generally most closely approximated by samples taken from the upper part of a buried soil (Matthews, 1984), and using either the humic acid fraction or total organic fraction (Martin and Johnson, 1995).

With respect to wood, or charcoal, a ^{14}C age estimate from an uncontaminated sample reveals the time period since the cessation of the cell respiration, and many of the problems related to bulk dating of soil organic matter can be ignored. However, the age estimate may vary with a magnitude of several hundred years depending on whether the sample is from the oldest or youngest annual rings. Payette and Filion (1993) pointed out that subarctic birch remains typically showed ages 200–450 BP at the time of burial. In terms of long-living pine trees, which may stay upright and be preserved long periods after their death, this matter should be appreciated. Even when dating charcoal, which had been isolated from surface soil, age estimates of the order of thousands of years may be attained, as demonstrated in Québec by Payette and Gagnon (1985). Charcoal is chemically inert and may be preserved for a long period in a soil matrix. It is thus possible that the topsoil obtains charcoal from several successive forest fires, perhaps of highly varying age, before burial. In such a case, conventional ^{14}C dating will produce an amalgam age without correspondence to any specific fire event. Therefore, radiocarbon age estimates from buried charcoal horizons are always older than the burial event (= maximum age for burial), and hence, any such single dates from a soil horizon should be interpreted with caution when relating them to local aeolian episodes. To facilitate comparisons between radiocarbon and luminescence techniques in this paper, ^{14}C ages have been calibrated following Stuiver and Reimer (1993), with a 50-year moving average (Stuiver and Becker, 1993).

Infra-red stimulated luminescence (IRSL) dating

Radiocarbon dating provides an age for organic matter present within a palaeosol or dune sand and therefore dates periods of vegetation growth and sand stability, yielding only an inferred age for sediment mobilization and dune accretion. Luminescence dating techniques are applicable to the quartz or feldspar grains of the sediment matrix and provide an age for deposition and burial of the grains. The use of luminescence techniques thus allows periods of aeolian activity and geomorphic change to be dated and IRSL has proved successful when applied to dune sands from the Mojave Desert (Clarke *et al.*, 1995; 1996; Rendell and Sheffer, 1996), southeastern Canada (Ollerhead *et al.*, 1994) and Ireland (Wintle *et al.*, 1998), showing good agreement with independent age control (Clarke and Käyhkö, 1997). The zeroing mechanism in luminescence dating is exposure to light. One of the advantages of IRSL techniques over more conventional thermoluminescence (TL) methods is the rapidity of bleaching of the signal with sunlight exposure. A recent study showed that 50% of the IRSL signal was zeroed in just 10 seconds direct sunlight whereas it would take around 30 minutes to remove the equivalent amount of TL (Clarke, 1996). Fast bleaching is useful in dealing with high-latitude sediments, which may have received limited light exposure prior to burial. In this study infra-red stimulated luminescence (IRSL) techniques were applied to potassium-rich feldspars obtained from the sands by sieving and heavy liquid density separation. Detailed description of the experimental methodology and results can be found in Clarke and Käyhkö (1997). Potential problems associated with luminescence dating of sediments, which have experienced soil-forming processes, include the unknown effect of grain weathering on the trapped signal and on the dose rate. Systematic studies on this topic are not available, and, thus, the age estimates acquired here are taken at their face value.

The study sites

Pine woodland

1) Petsimjärvi-Kiellajoki, Finland

The Petsimjärvi-Kiellajoki glaciofluvial-glaciolacustrine succession was deposited in a glacial lake during the inland ice deglaciation. The main dune complex was formed adjacent to an esker, mainly by winds blowing from the WNW–NW (Seppälä, 1971; 1980). Presently, active aeolian surfaces are located on the original dune crests and the primary glaciofluvial deposits (Figure 3).

Two sections were sampled and investigated in detail at Petsimjärvi, one at the margin of the largest dune blowout in the area, and the other at the margin of the largest glaciofluvial delta top blowout. The former section was investigated at the dune nose region on the former stoss slope with only one unambiguous palaeosol. The lee slope section showed several truncated charcoal horizons, probably due to redeposition of material, and was disregarded. The dating strategy (cf. Figure 4) consisted of a ^{14}C sample of charcoal from the buried former dune surface at a depth of 1.15 m (Table 2), and two sand samples for IRSL dating from above and below the palaeosol (Table 3). The sand sample from below the charcoal horizon yielded an age estimate of 6.28 ± 0.59 ka (cf. Table 3) reflecting active deposition of the initial dune material. The charcoal-bearing horizon capping the soil yielded an age estimate of 1600 ± 90 BP (Beta-80424), or 1510 (1550–1390) cal. BP (cf. Table 2), while on the basis of the upper IRSL sample the burial of the soil had commenced at this point by 0.58 ± 0.06 ka.

The other blowout section on the glaciofluvial delta was located some 3 km NW of the dune site. Due to the coarse glaciofluvial material and surface lag formation, the blowouts on the delta are

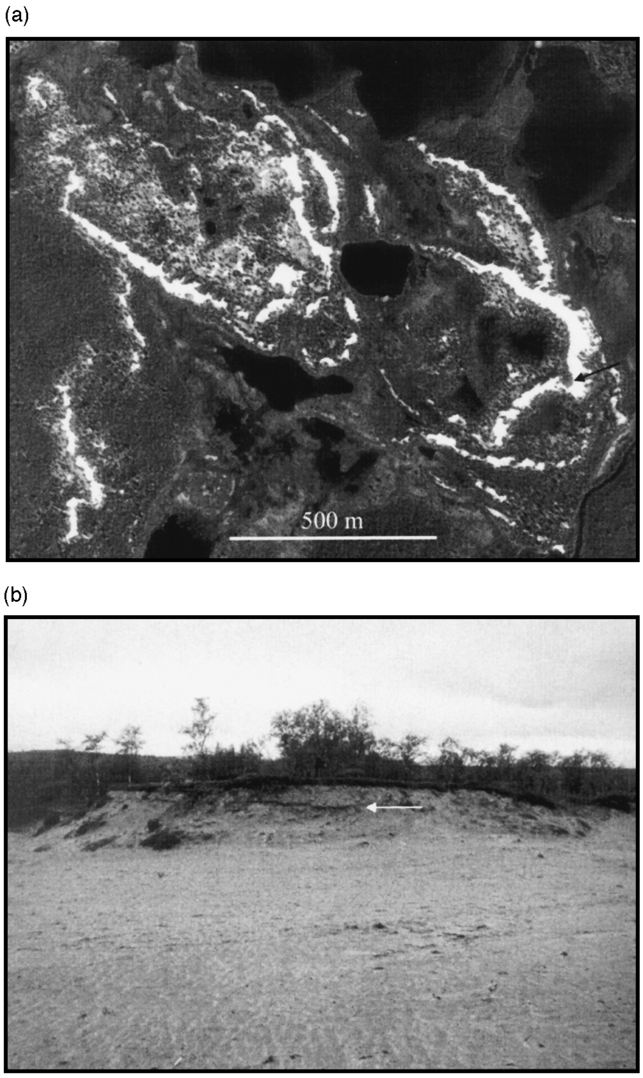

Figure 3 (a) Aerial photograph (9331/181) of the Petsimjärvi dunefield showing 'pearl necklace blowouts' (cf. Käyhkö, 1997) at parabolic dune crests. The arrow shows the location of the logged section. Copyright: Topographic Division of the Finnish Defence Forces. (b) A view across a typical blowout at Petsimjärvi. A buried soil horizon (arrow) crops out of the basin margin.

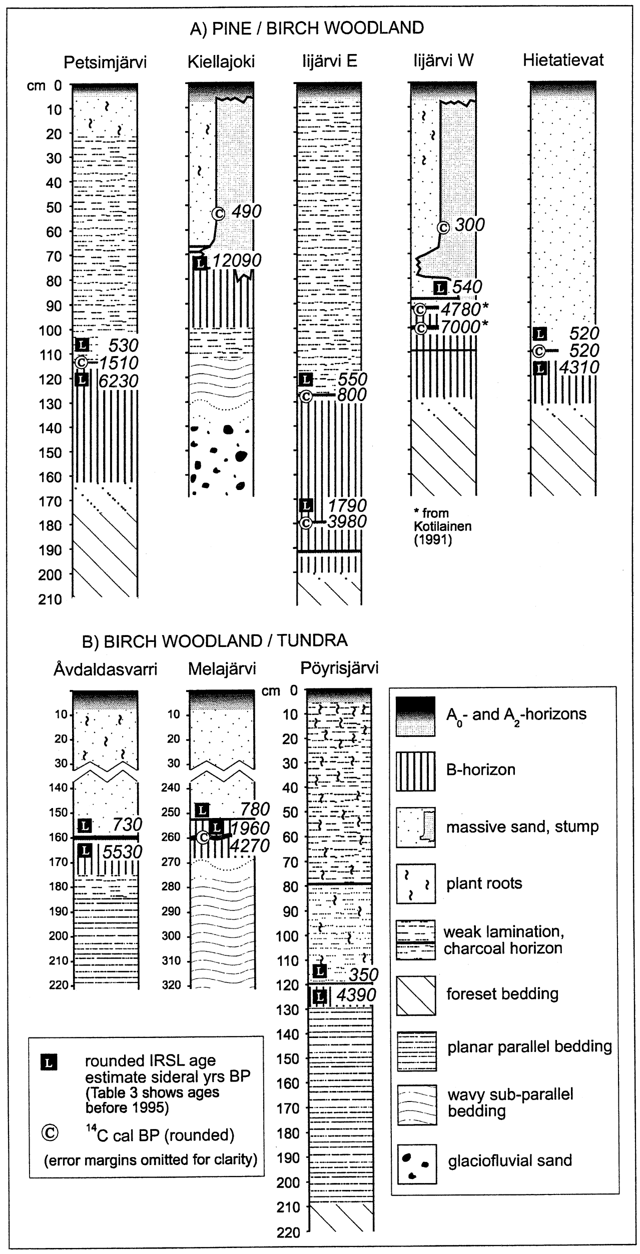

Figure 4 Stratigraphic logs of the studied aeolian deposits and associated palaeosols. Iijärvi E and Iijärvi W denote eastern and western edge of the studied blowout.

shallow and the allied adjacent marginal deposits small in volume. The glaciofluvial unit consisted of well-rounded scattered clasts up to 100 mm in diameter within a matrix-supported sand capped by a buried podsol soil 0.7 m below the surface (cf. Figure 4). Coincident with this buried soil, a subfossil pine stump with fire scars was found in the life position.

The IRSL age estimate from the top of the primary delta deposit was 12.130 ± 2.095 ka, and is believed to reflect the time of the regional deglaciation. The comparatively large standard deviation of the IRSL age estimate is related to the grain-size fraction used for dating (cf. Clarke and Käyhkö, 1997). The radiocarbon sample from the outer rings of the pine stump gave an age estimate of 490 (520–450) cal. BP. As the stump was *in situ*, and the dated tree-rings had fire scars, it is reasonable to assume that the location suffered a forest fire some 500–570 years ago. Clearly, the deposition of aeolian material around the pine commenced only after this event. However, the possibility that the aeolian activity may have begun in the region at an earlier date cannot be eliminated. Based on the available data, the late-Quaternary history of the Kiellajoki region can be summarized as follows.

(1) Deglaciation at around 12 ± 2 ka, based on the IRSL age estimate from the glaciofluvial delta.

(2) Limited aeolian activity on the coarse glaciofluvial delta sediments after the draining of the glacial lake (Kiellajoki area). A major dunebuilding episode on the finer substrate on the eastern side of the esker-delta complex (Petsimjärvi area), which lasted at least until about 6 ka in places. The stabilization of the dunefield was probably a diachronous event, being governed by local conditions. This view gains support from the fact that the present dunes to the north of the Kiellajoki river are stable, whereas those to the south are widely deflated.

(3) The re-deposition of aeolian material commenced at the study sections 500–600 years ago. This is a minimum age for the beginning of the latest aeolian episode.

2) Iijärvi, Finland

Some 40 km to the east of Kiellajoki-Petsimjärvi lies the Iijärvi dunefield, located at the southern end of Lake Iijärvi. The field is associated with one of the longest eskers in Finnish Lapland. Investigations focused on the largest dune, which possessed a

Table 2 List of the radiocarbon age estimates obtained in this study. Calibration was based on UWTEN93.14C calibration file (Stuiver and Reimer, 1993) with a 50-year moving average (Stuiver and Becker, 1993)

Lab. code	Locality	Age BP	Cal. age BP	Age range 1σ	Age range 2σ
Beta-80421	Hietatievat	490 ± 50	522	536–505	549–475
Beta-80422	Iijärvi 3rd soil	920 ± 50	804	921–751	940–715
Beta-80423	Iijärvi 2nd soil	3690 ± 80	3977	4143–3886	4241–3818
Beta-80424	Petsimjärvi	1600 ± 90	1511	1554–1387	1702–1303
Beta-80425	Iijärvi stump	260 ± 80	297	443–0[1]	528–0[2]
Beta-80426	Kiellajoki stump	410 ± 50	488	516–451	528–313
Beta-80427	Melajärvi	3870 ± 70	4266	4397–4163	4428–4074

[1] age range obtained from intercepts: 443–366, 334–278, 6–0*
[2] age range obtained from intercepts: 528–278, 6–0*

Table 3 List of the luminescence age estimates obtained in this study

Sample	Locality	Total dose μGy/a	ED (Gy)	Age (years)	Rounded age
1	Petsimjärvi	2267 ± 174	14.23 ± 0.75	6277 ± 584	6275 ± 585
2	Petsimjärvi	2829 ± 188	1.64 ± 0.11	580 ± 54	580 ± 55
3	Kiellajoki	2586 ± 294	31.36 ± 4.08	12128 ± 2095	12130 ± 2095
4	Iijärvi E	2658 ± 163	1.58 ± 0.05	594 ± 41	594 ± 40
5	Iijärvi E	2749 ± 164	5.05 ± 0.14	1837 ± 120	1835 ± 120
6	Iijärvi W	2750 ± 167	1.60 ± 0.12	582 ± 56	580 ± 55
7	Hietatievat	3826 ± 228	2.15 ± 0.16	562 ± 53	560 ± 55
8	Hietatievat	3795 ± 227	16.51 ± 0.68	4350 ± 315	4350 ± 315
9	Åvdaldasvarri	2367 ± 120	1.83 ± 0.10	773 ± 57	775 ± 60
10	Åvdaldasvarri	2080 ± 115	11.60 ± 0.80	5576 ± 492	5575 ± 490
11	Melajärvi	3069 ± 172	2.53 ± 0.18	824 ± 74	825 ± 75
12	Melajärvi	3060 ± 162	6.13 ± 0.31	2003 ± 146	2005 ± 145
13	Pöyrisjärvi	3793 ± 256	1.47 ± 0.11	388 ± 39	390 ± 40
14	Pöyrisjärvi	3538 ± 197	15.68 ± 0.67	4432 ± 311	4430 ± 310

straight middle part with arms slightly pointed towards the palaeowind. The crest of the dune is occupied by a large deflation basin some 460 m long and 50 m wide, with a basin depth of almost 6 m (as measured from the top of the redeposited rim). This is the largest blowout in the area, and is part of an almost 2-km-long chain of deflation hollows (classified as a *pearl necklace blowout*; Käyhkö, 1997) running along the crest of the dune ridge. The section on the eastern (leeward) side of the basin (cf. Figure 4) included three stacked buried palaeosols. Visually, the middle soil was the best developed and also had the most abundant soft-rock deformation structures. Charcoal from this horizon was sampled for ^{14}C dating, and an age estimate of 3690 ± 80 BP (Beta-80423), or 3980 (4140–3890) cal. BP obtained.

Overlying the middle palaeosol was a massive sand bed 0.5 m thick. An IRSL sample from the base of this bed yielded an age estimate of 1.84 ± 0.12 ka. The whole of this unit showed weak illuviation, apart from the thin A_2 horizon. The dip of the top buried soil surface was 21° towards 35°N (NE), suggesting that the unit pinched out away from the blowout. Radiocarbon dating of the charcoal layer capping this unit yielded an age estimate of 920 ± 50 BP (Beta-80422), or 800 (920–750) cal. BP. An IRSL sample from the topmost unit gave an age estimate of 0.60 ± 0.04 ka. This date reflects the commencement of deposition in the latest phase of activity at the sampling point. The thickness of the topmost unit at the section was almost 1.3 m, but decreased rapidly away from the margin.

Some 100 m to the south of the above section, on the western side of the basin, a buried subfossil pine stump cropped out following lateral growth of the blowout (Figure 4). This stump is probably the one described by Kotilainen (1991) who obtained ^{14}C age estimates of *c*. 7000 cal. BP and 4800 cal. BP (cf. Figure 4) from the two lowermost charcoal horizons. All the palaeosols adjacent to the stump dipped 15° towards 260°N (W), hence they probably represent earlier dune stoss slope surfaces. Unlike the pine stump found at the Kiellajoki delta, the Iijärvi pine lay slightly above the buried soil with some 0.15 m of sand being deposited prior to seedling growth. The mildly charred stump was 0.3 m in diameter at the base, suggesting an age of at least 100 years prior to death.

Two age estimates were obtained from this section. An IRSL sample from the thin redeposited sandbed between the base of the stump and the underlying charcoal horizon yielded an age of 0.58 ± 0.06 ka. A radiocarbon sample from the outermost preserved rings of the pine stump gave an age of 260 ± 80 BP (Beta-80425), or 300 (450–0) cal. BP. In summary, the proposed aeolian sequence at Iijärvi is as follows.

(1) An initial dunebuilding phase, the end of which was not dated.
(2) A stable phase until at least 7 ka.
(3) An aeolian episode, during which the whole dunefield was not necessarily activated.
(4) A soil-forming phase.
(5) A forest fire (or several fires) in the region at around 4.8–3.9 ka, which may have triggered an aeolian episode.
(6) Aeolian activity some 2000–1700 years ago.
(7) An anchored phase.
(8) A forest fire not earlier than 1000–800 years ago possibly led to a further aeolian episode.
(9) The beginning of sand deposition around the basin commenced at around 600 years ago and continues today.

3) Hietatievat, Finland

Numerous literature references, both scientific and popular, discuss the abundant aeolian activity that can be found at Hietatievat (e.g., Ohlson, 1957; Seppälä, 1966; 1974; 1984; 1995; Tobolski, 1975; Punkari and Varjo, 1977; Vliet-Lanoë *et al.*, 1993; Käyhkö, 1994). Earlier ^{14}C and TL dates (Vliet-Lanoë *et al.*, 1993; Seppälä, 1995) suggest that the primary aeolian stabilization commenced *c.* 7 ka (cf. Figure 2). In addition to the numerous small dune crestal blowouts, large subspherical deflation basins (classified as *tray basins*; Käyhkö, 1997) have been scoured into the sediment plateau. A few scattered pine trees grow on a broadened esker, and a mature pine forest can be found a few kilometres to the south along it.

The blowout study site lies in the northern part of the Hietatievat locality. It consists of two open basins, with several butte-type erosion remnants supporting mountain birch and juniper scrub. It is highly irregular in shape and does not seem to follow a primary dune. A section was cleaned in the northern rim deposit to reveal the stratigraphy, (cf. Figure 4). The lowermost exposed facies consisted of dune foreset beds dipping at 32° towards 330°N (NNW). This unit was capped by a buried podsol soil at a depth of 1.1 m. The subhorizontal A_0 horizon was underlain by a 30 mm thick A_2 horizon and a mottled B horizon.

Three age estimates were obtained from the section. A radiocarbon sample was collected from the buried charcoal horizon, and IRSL samples from both below and above the palaeosol. The lowermost luminescence sample yielded an age estimate of 4.35 ± 0.32 ka. This depicts the end of the dune deposition episode. The radiocarbon age estimate from the charcoal horizon was 490 ± 50 BP (Beta-80421), or 520 (540–500) cal. BP, which approximates to the time of the forest fire. Above this, the luminescence sample produced an age estimate of 0.56 ± 0.06 ka, which is practically indistinguishable from the soil radiocarbon age. Hence, it suggests that the deposition at this point started shortly after a forest fire. The aeolian history can therefore be summarized as follows.

(1) An initial dunebuilding phase that continued until *c.* 4.3 ka. Moist interdune areas were probably vegetated earlier, perhaps commencing at around 7 ka.
(2) A subsequent period of general stability, but with numerous forest fires and local aeolian activity until approximately 0.6–0.5 ka.
(3) Commencement of the current aeolian episode in the form of crestal activity and a few larger blowouts, but no migrating dunes.

Mountain birch woodland

4) Åvdaldasvarri, Norway

The Åvdaldasvarri dunefield is the largest area of inland aeolian activity in northern Norway (Käyhkö *et al.*, 1996) and lies almost exactly on the 70°N parallel (Klemsdal, 1969; Sollid *et al.*, 1973). Glaciofluvial-glaciolacustrine-aeolian sands extend from 280 to 350 m above sea level, and abundant, mature parabolic dunes have developed. The form of the dunes indicates a northwesterly effective palaeowind direction. A total of 35 ha of currently active aeolian surfaces was detected in the region. On the initial parabolic dunes, aeolian processes have produced numerous scattered small blowouts.

All the sections examined had only one unambiguous buried soil. In interdune areas with moist conditions, signs of frost action were detected. Sampling was undertaken at the margin of the largest local blowout, some 30 m in diameter and 4 m in depth. The original dune surface had been buried under a 1.6-m-thick bed of redeposited sand (cf. Figure 4). The underlying aeolian strata showed subhorizontal planar parallel bedding within moderately sorted fine sand. Two luminescence samples were collected from the section, one immediately below and another one above the buried soil. The soil did not contain enough macroscopic charcoal for conventional ^{14}C dating. The top of the lower, original aeolian unit yielded an IRSL age of 5.58 ± 0.49 ka, whereas the deposition of the marginal deposit had commenced at this point at 0.78 ± 0.06 ka.

These data suggest that the dune in question had become fully stabilized not earlier than approximately 5.5 ka. No signs of subsequent activity have been preserved, but this should not be taken as evidence eliminating the possibility of such events. Nevertheless, subsequently the dune became deflated about 780 years ago. In summary, the inferred aeolian history is as follows.

(1) An initial dunebuilding phase that continued until about 5.5 ka at locations suitable for aeolian transport. Moist interdune areas may have been vegetated earlier.
(2) A subsequent period of general stability existed until approximately 0.8 ka.
(3) The beginning of the currently active aeolian phase, possibly caused by fire in the region. A faint charcoal horizon with only a small amount of charcoal, however, suggests that little vegetation was burned during the fire event(s).

5) Melajärvi, Finland

Melajärvi is located in the far northwest of Finland, close to the border with Norway. The area is north of the current Scots pine tree line by several tens of kilometres, at the transition zone between birch scrub and treeless tundra. The dunes are located adjacent to an esker widening on the proximal side of a watershed at the border with Norway.

The locality is the largest presently active parabolic dune *sensu stricto* in Lapland, indicating an effective wind direction from the WNW. The adjacent well-formed parabolic dune blowout is the second largest active deflation basin in Lapland, being some 300 m wide and 600 m long, with an area of 12 ha (Käyhkö *et al.*, 1996). A buried soil horizon crops out along the almost horizontal sand surface within the blowout marked by a line of tufted *Festuca* sp. grasses. Also protruding from the sand surface are trunks of mountain birches, which are now being exposed on the stoss slope as the migrating dune passes the site. In the middle of the blowout there are two outcrops of silt-sized material with occasional pebble and boulder clasts. This silt bed was found to crop out in various parts of the area and is likely to be of glaciolacustrine origin. Due to the high resistance of the silt bed to wind erosion, the flat-topped outcrops stand 1–1.5 m above the surrounding sand surface, with the largest being some 100 m in diameter. The exposed silt bed is partly covered by an algal crust and plants including *Salix* spp., *Juncus trifidus* and *Polytricum piliferum*, which further increase the resistance of the surface to wind action.

A detailed study of the surficial deposits was undertaken at the northern edge of the blowout (Figure 4). This location is currently the left arm of the dune, and the thickness of the redeposited sand rim at the logged site is 2.5 m. Neither the glaciofluvial gravel nor the glaciolacustrine silt bed was exposed, but some 10 m to the west of the section the silt bed was found at 0.8 m depth beneath the topmost buried organic horizon. The top of the silt bed was undulating but sharp. Covering the silt unit was a bed of fine sand with weak wavy, parallel and subhorizontal strata with abundant deformation structures. The top of this unit exhibited overturned fold structures probably related to a fallen tree. There are no published data of past pine colonization in this area, but it is reasonable to assume that pine has grown here in the past, as it is currently found only 30 km to the south. Eronen's (1979) study obtained age estimates from subfossil pine trunks from an elevation some 40 m higher. In general, the pine limit in the

Enontekiö region during the warmer mid-Holocene is believed to have been around 500 m (Eronen and Huttunen, 1993).

The organic horizon capping this unit was sampled for radiocarbon dating, and yielded an age estimate of 3870 ± 70 (Beta-80427), or 4270 (4400–4160) cal. BP. This estimate gives a maximum age for the soil burial event, i.e., not earlier than approximately 4300 years ago. The 80-mm-thick redeposited aeolian sandbed above the organic horizon produced an IRSL age estimate of 2.01 ± 0.15 ka. Between this bed and the latest redeposition, within which no visible sedimentological discontinuities were observed, lay the second organic horizon. This organic layer has dip and strike similar to the lower horizon. The charcoal in this horizon was so fine-grained that it was not suitable for conventional radiocarbon dating. However, the sandbed above the organic horizon was dated directly using the luminescence technique, and an age estimate of 0.83 ± 0.08 ka obtained. In summary, the local Melajärvi aeolian episodes consist of the following.

(1) An initial aeolian phase, the end of which was not dated.
(2) A subsequent stable phase which did not cease before 4.2–4.5 ka, as this is the maximum age for the burial of the charcoal-bearing soil.
(3) Subsequent deposition of aeolian material commenced about 2 ka BP, which is the minimum age for the beginning of the aeolian phase.
(4) Another stable phase, although probably on the dune arms only, ended no later than 800 years ago.
(5) A continuous episode of aeolian activity from at least 800 years ago until the present.

Treeless tundra

6) Pöyrisjärvi, Finland

The Pöyrisjärvi region exhibits the largest concentration of present-day aeolian activity in the whole area under investigation with some 250 ha of barren surfaces (Käyhkö *et al.*, 1996). This is several kilometres beyond the pine tree-line, with mountain birch only surviving in sheltered places. A section 2.2 m deep was excavated through the steep cliff in the marginal deposit at the western (windward) edge of the largest deflation basin (14 ha) (Figure 4). The section contained three distinctive sedimentary units. The lowermost unit consisted of cross-bedded strata of fine sand dipping 24° towards 50°N (NE). The upper bedding plane of this lower facies was erosional, forming an angular unconformity with the overlying horizontal strata. The overlying bed, consisting of horizontal parallel laminae defined by grain-size variations, was 0.9 m thick but pinched out westwards within a few metres. An IRSL sample from the top of this unit yielded an age estimate of 4.43 ± 0.31 ka, which approximates to the termination of deposition of the unit. A distinctive podsol soil caps the facies, indicating a non-depositional episode. However, deposition recommenced again some 400 years ago (IRSL age estimate 0.39 ± 0.04 ka), and since then 1.2 m of redeposited aeolian sand has accumulated over the buried soil. The deposition of this youngest unit has been rapid, probably due to an abundant sediment source from the blowout. A weak charcoal-stained layer could be detected within the redeposited unit at 0.8 m depth, probably signifying a minor fire event. An attempt to collect enough charcoal from the soil horizon for conventional ^{14}C assay was unsuccessful. The apparent sequence of aeolian events at Pöyrisjärvi can be summarized as follows.

(1) An initial duneforming episode with migrating parabolic dunes, the end of which was not dated.
(2) A change in the deposition pattern from foreset bedding to horizontal bedding (with a possible hiatus) with deposition ending at approximately 4.4 ka.
(3) A subsequent soil-forming period, followed by a fire in the region at least some centuries later, which may have triggered aeolian activity and the growth of a blowout in the vicinity.
(4) Onset of rapid aeolian deposition no later than at about 0.4 ka, continuing to the present.

Summary of the results

Four IRSL samples were taken from deposits interpreted as first phase aeolian depositional units due to their distinctive bedding and an absence of soil formation underneath. The four IRSL age estimates obtained were: 6275 ± 585 (Petsimjärvi), 4350 ± 315 (Hietatievat), 5575 ± 490 (Åvdaldasvarri), and 4430 ± 310 (Pöyrisjärvi). However, the IRSL age estimates for Pöyrisjärvi should be viewed cautiously, as the dated horizontally bedded unit lay unconformably on top of the dune foreset bed.

These data suggest that the termination of early-Holocene aeolian activity was probably not a synchronous event across Lapland. In addition, the above ages are somewhat younger than previously published estimates (cf. Seppälä, 1971; Kotilainen, 1991; Tikkanen and Heikkinen, 1995). All of the above sections described by these workers have only one palaeosol buried by redeposited material derived from the deflation basin scours. However, for example at Iijärvi, at least three stacked buried soils were detected in the marginal deposits. Even though the complete history at Iijärvi may not be recoverable due to the early deposits being destroyed during blowout growth, the soil succession enables the timelag between the soil radiocarbon ages and the overlying sand IRSL ages to be assessed.

The apparent hiatus between the radiocarbon age estimate from the second buried soil and the base of the overlying sandbed was roughly 2000 years. The equivalent gap in the case of the third soil was approximately 300 years. In addition to Iijärvi, the dating procedure employed at two other locations allows similar comparisons. At Pöyrisjärvi and Åvdaldasvarri, not enough charcoal could be extracted from the soil for conventional ^{14}C dating to enable comparisons with IRSL age estimates from the redeposited sand units. The ages were: 390 ± 40 (Pöyrisjärvi), 775 ± 60 (Åvdaldasvarri), 825 ± 75 (Melajärvi), and 580 ± 55 (Iijärvi west side).

The seven IRSL dates from the base of the redeposited beds cover a period of 900–350 years, or between AD 1095 and 1645, error margins included. Further evidence for deflation initiation was gained from two ^{14}C age estimates; first, 490 (520–450) cal. BP from the pine stump buried in redeposited sand at Kiellajoki glaciofluvial delta, and second, an age of 300 (450–0) cal. BP from a similar stump at Iijärvi.

The above results suggest that interpretations of the timing of the beginning of an aeolian episode will, in most cases, be markedly different depending on whether they are based on IRSL or ^{14}C age estimates. The above IRSL data suggest that the current aeolian episode dates back only a few centuries, and started fairly simultaneously across the study area.

A diagrammatic summary of the evidence for the timing of aeolian episodes obtained in this study is shown by Figure 5, while Figure 6 combines the new results with those of earlier studies. The stabilization of the initial dunes seems to have occurred at least from about 7.5 to 4.4 ka, and suggests influence by both regional and local factors such as pine coverage and overall humidity. Recurrent activity, as evidenced by stacked buried soil horizons, seems to have taken place only in the well-established pine forest. Sites presently well outside the pine zone typically have only one buried soil. Although there is considerable variation in the ^{14}C age estimates obtained from the topmost buried charcoal horizons, all IRSL ages from the basal parts of

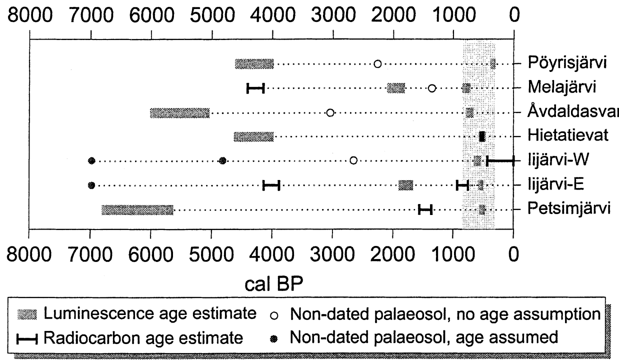

Figure 5 Summary of age estimates obtained in the present study. The grey shaded area shows the beginning of the latest reactivation episode across the study area.

the most recently deposited units show similar ages within the range 900–350 years ago, reflecting the onset of the current aeolian phase.

Discussion

The dunebuilding period

Lapland floral biostratigraphy (Seppä, 1996) suggests that the climate during the early Holocene was warmer and also moister than at present. It took about 400 years for birch to respond to the warmer climate, and a further 1000 years before birch had colonized practically the whole of northern Fennoscandia, by approximately 10 000 cal. BP. The birch forest ground layer was dominated by grasses, lycopods and ferns. Gradually, this lush layer disappeared due to pine colonization from the north and east plus a simultaneous climate change towards drier conditions. In northernmost Norway, pine was already present at around 10 290–10 000 cal. BP (Hyvärinen, 1975; Seppä, 1996). The Lake Inari region was colonized around 8500–8000 cal. BP (Seppä, 1996), and finally, the Pöyrisjärvi region in the northwestern Finnish Lapland was reached as late as 6800 cal. BP (Mäkelä *et al.*, 1994). However, low absolute concentration of pine pollen within the lake sediments suggests that a fully developed pine forest may never have existed at Pöyrisjärvi. The total timelag is around 3500 years. Seppä (1996) concluded that the complex nature of pine migration cannot be explained by climate alone and that biological migrational factors seem to have played a considerable role in the process.

The tree-lines started to decline at around 6000–5500 cal. BP, and this period is generally considered to herald a major environmental change after the warmer episode. Forest retreat was accompanied by an extension of tundra vegetation. The late-Holocene tundra, however, was markedly more humid than its dry lateglacial equivalent. Seppä (1996) suggests that high values of Cyperaceae, *Trollius europaeus*, *Rubus chamaemorus*, etc, indicate moist soil conditions and a gradual expansion of peatlands. The observed changes in vegetation correlate well with the suggested rise of groundwater level in Lapland at around 5000–4000 BP (Seppälä, 1971; Hyvärinen and Alhonen, 1994; Zetterberg *et al.*, 1994). The reasons for the rise of water table due to a moister

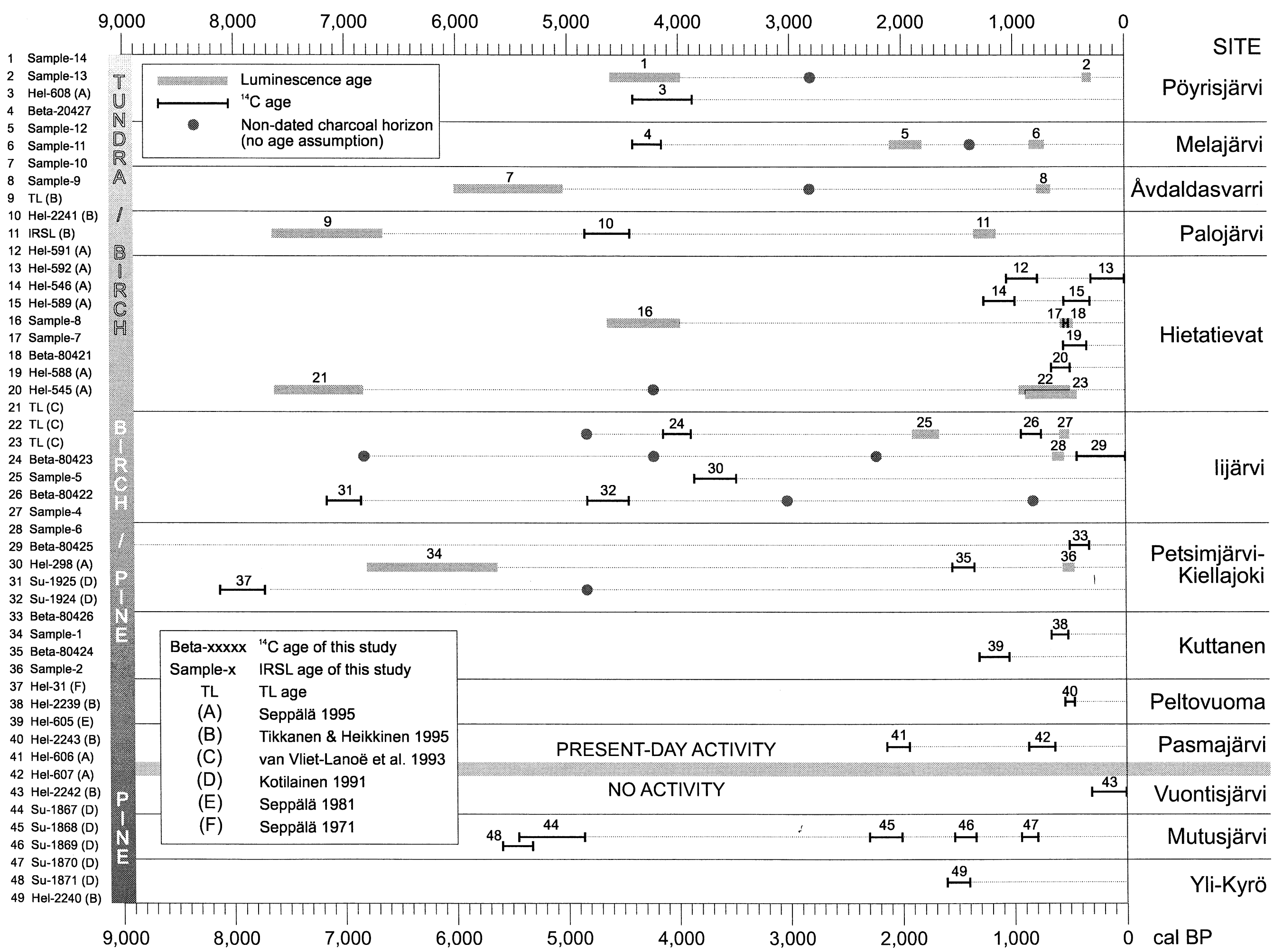

Figure 6 Summary of all age estimates presently available from aeolian deposits in northern Fennoscandia.

climate are not well understood in terms of quantitative estimates of the behaviour of precipitation and evaporation. In practice, falling temperatures alone would result in higher moisture through decreased evaporation. The dramatic rise in lake levels and the simultaneous initiation of peatlands in the warmer environment of southern Finland (Korhola, 1995) suggest that falling temperatures were accompanied by increased precipitation.

The current view of the early-Holocene climate as relatively warm and moist contrasts markedly with the earlier hypotheses, which considered the Pre-Boreal substage as being more similar to periglacial in terms of climate (e.g., Seppälä, 1971). In the light of rapid deglaciation after the Younger Dryas, such a cold climate appears improbable. The first hypotheses supporting cold climates were based solely upon biostratigraphical evidence, which is now known to suffer from a marked timelag. Hence, the view that 'strong winds under periglacial conditions' (Seppälä, 1995) initially formed the dunes in the study area appears less likely in the light of more recent proxy data. Reasonably moist conditions, and possibly a partial grass cover, could explain the parabolic form of the dunes. David (1979) considered sand moisture content as an important factor in the parabolic dunebuilding process. He included all parabolic dunes into the 'wet-sand' category, with moisture contents typically between 4 and 8% (David, 1996).

Previously, dune stabilization has been simply related to birch and pine colonization together with rising temperatures, around 8000–7500 BP (Tikkanen and Heikkinen, 1995). The subsequent warm Atlantic substage and allied pine colonization encouraged a belief that, generally, dune stabilization occurred across northern Fennoscandia. Yet the latest data on pine colonization suggest diachronous pine migration across northern Fennoscandia (Mäkelä *et al.*, 1994; Seppä, 1996), as discussed above.

Despite the similarities in the trends of pine colonization and dune stabilization, the two events did not occur simultaneously. The fact that pine is known to have reached its widest distribution earlier (1–2 ka) than when the dunes became stable suggests that regionally, during the early Holocene, pine was unable to inhibit aeolian activity, unlike the present situation (cf. Käyhkö *et al.*, 1996). Cold-climate dunes are known to be sensitive to moisture, e.g., David (1977), Koster (1988) and Seppälä (1995). When considering the dune stabilization data for Lapland, the youngest age estimates at around 4.4 ka cal. BP correlate well with the increasing humidity. However, it has to be stressed that the reconstructed aeolian history of northern Fennoscandia remains incomplete.

Keeping in mind the limitations of the present data, it is suggested here that many dunefields became completely anchored not in the course of pine colonization but somewhat later, when a change to cooler and moister climate resulted in increasing soil humidity. Pine colonization was accompanied by dry drifting sands that were devoid of trees, despite the fact that the species existed in the near vicinity. In areas where dense pine forest surrounded the dunes and was able to change the aerodynamic properties, or where the soil was wetter, for example in interdune areas, the sand became anchored. When the potential source areas for aeolian material were colonized, the sediment supply would be reduced and gradually the dunes were anchored. It has to be emphasized that migrating dunes are extremely rare in Lapland at present. In the light of the regional distribution of basal ages, it is possible that the invasion of dense pine caused dune stabilization in lowland areas. These areas include the dunefields at Kiellajoki-Petsimjärvi and Iijärvi. Areas devoid of a fully established pine forest remained at least partly active for much longer.

Recurrent activity during the Holocene

Many palaeoclimatic reconstructions covering this period in Fennoscandia have been made using different techniques, such as pollen (e.g., Hyvärinen, 1993), tree macrofossils (e.g., Eronen and Huttunen, 1993; Kullman, 1993), glacial geomorphology and stratigraphy (Griffey and Worsley, 1978; Matthews, 1991) and periglacial sedimentology (e.g., Worsley and Harris, 1974; Elliott, 1996). A particularly cold period known as the Late Neoglacial or 'Little Ice Age' (LIA) has occurred during the last 600 years, between *c.* AD 1300 and 1900.

Seppälä (1995) suggested that a deflation phase started at the early Sub-Boreal substage, approximately 4800 BP. In contrast, the present study suggests that there was no large-scale dune reactivation during the mid-Holocene as a response to forest decline, but rather the dunes were stable or became stabilized due to increasing humidity. Numerous buried charcoal horizons within the pine forest zone (e.g., Mutusjärvi, Iijärvi) from this period indicate frequent forest fires followed by short-lived aeolian episodes. There is, however, no preserved evidence for widespread dune activity in Lapland during this period.

Dunefields far outside the present pine zone generally only have one or two buried charcoal horizons, whereas dunes both at the pine margin and inside the pine zone have several layers of buried charcoal, for example at Iijärvi and Mutusjärvi (Kotilainen, 1991). This pattern suggests that in areas favourable for pine growth the alternating interplay of vegetation and aeolian dominance produces a succession of active and stable periods, and associated cyclicity in the sedimentary record. Away from the present pine zone, the preserved stratigraphic evidence suggests that the passing of an ecological threshold led to less favourable conditions for a healthy forest cover. Fire may have destroyed the vegetation cover and triggered aeolian activity. Once initiated, activity continued as the pre-fire vegetation was unable to recover. The presence of only one preserved buried soil in the stratigraphy does not exclude the possibility of other inactive periods, the evidence for which was lost as the blowout grew laterally. In parallel with the conclusions of Payette and Gagnon (1985) in Québec, it is also possible that in Lapland fire frequency within well-established pine forests has been higher than that closer to the tree-line.

The latest aeolian episode

The IRSL data suggest that the current aeolian episode started roughly between AD 1100 and 1650 across the study region. Charcoal ages suggest both an earlier commencement and greater time spread for the episode. However, ^{14}C ages give the maximum age for soil burial in contrast to IRSL ages, which represent the minimum age for the beginning of aeolian activity. The regional age distribution for the beginning of the current aeolian episode is shown in Figure 7. The oldest age, from the birch woodland at Melajärvi of some 825 years contrasts with the youngest age at Pöyrisjärvi in the treeless tundra of some 390 years. No clear regional pattern in the ages can be discerned with the present data.

The overall consistency of the age estimates is believed to reflect a major change in the environment after 800 BP. Whether this change was human-induced or natural has to be considered carefully. Bergqvist (1981), for example, concluded that in most cases the reason for the present-day activity is unknown. Either the change itself was abrupt, or the aeolian response arose from a gradual change of the threshold-type. The fact that dunes from different climatic-vegetational regimes experienced deflation practically simultaneously makes the threshold-type response somewhat doubtful.

The observed near-synchronous commencement over a wide area might, in principle, suggest a climatically induced process. This view gains support from studies by Filion (1984) and Filion *et al.*, (1991) in Canada, as well as Eisner *et al.*, (1995) in Greenland. The latter workers reported a significant increase in aeolian sand and silt deposition in a west Greenland lake about 1000 BP with a possible climatic control. A number of the ages fall within the LIA event, but many dates actually precede the cooling by some centuries, and, as this is also present in North America and Greenland, perhaps aeolian sediments have reacted to some other

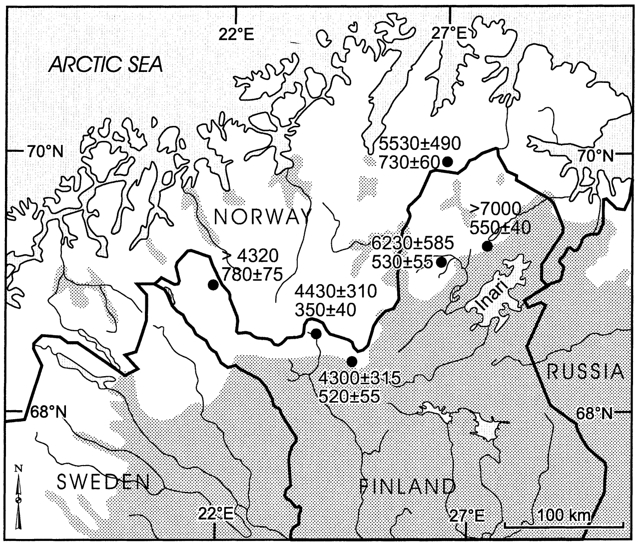

Figure 7 A compilation map showing the proposed timing of initial dune stabilization and the beginning of the present phase of aeolian activity at each study locality. At Iijärvi the age for initial dune stabilization is based on Kotilainen (1991). At Kiellajoki, Seppälä (1971) has obtained a ^{14}C age 7160 ± 200 BP from buried charcoal (cf. Figure 2) suggesting stabilization of the dunefield before this time.

factor. The pine decline in Lapland seems to have taken place gradually during the last millennium (e.g., Eronen and Huttunen, 1993), which suggests that dune areas outside pine forest remained anchored for a substantial period before becoming deflated. Hence, pine forest changes do not fully explain the trend, despite the suggested present-day control on the process. Changes in humidity may, again, offer an explanation; e.g., Vliet-Lanoë *et al.*, (1993) suggested that the dune remobilization at Hietatievat corresponded to a general lowering of the water table. A similar lowering of the groundwater level, however, has not been recorded by, for example, Hyvärinen and Alhonen (1994) in western Lapland.

Conclusions

With the aid of combined IRSL and ^{14}C dating, in conjunction with interpretation of stratigraphical data, the following preliminary conclusions can be drawn. The initial dunes were active for several millennia after the last regional deglaciation, and stabilization did not take place simultaneously. The stabilization process appears likely to have been diachronous at both local and regional scales. The first areas stabilized were local interdune areas and regional dunefields colonized early by pine. This stabilization took place generally before 7 ka. Local large dunes and regional dunefields colonized late by pine (if at all) became stable only around 4.3 ka, when the climate became more humid and the groundwater table rose. The range of dates suggests that the full pattern has yet to be established.

The latest episode of aeolian activity, which, with few exceptions, only occurs as localized activity, dates to about 0.90–0.35 ka, or AD 1100–1650 across the study area. No clear regional pattern is observable in the commencement of deflation, but this may be due to the small number of dates. A unique deflation triggering factor could not be identified, suggesting that several agents may have acted together. Climatic-vegetational parameters, especially the ‘Little Ice Age’, together with reindeer trampling, serve as a potential combination of factors responsible for the continuing aeolian activity at the tundra sites. At the pine forest zone margins, forest fires may have played an important role in aeolian reactivation, but further work is required to clarify their importance.

Acknowledgements

This work was undertaken as part of PhD research by JAK at the University of Reading. It was funded by the British Council, Emil Aaltonen Foundation, The Academy of Finland (projects 1012238 and 2247), Maj and Tor Nessling Foundation, Alfred Kordelin Foundation, University of Helsinki, and The University of Turku Foundation. MLC conducted the IRSL dating at the University of Wales, Aberystwyth. Mr Sakari Palo gave invaluable help in the field. Thoughtful reviews by Louise Filion and John Matthews greatly improved the manuscript.

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