The European sand-belt in Eastern Europe and comparison of Late Glacial dune orientation with GCM simulation results

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The European sand belt in eastern Europe – and comparison of Late Glacial dune orientation with GCM simulation results

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A compilation is presented of the continuation of the European sand belt, east of Poland. Dune fields encompass most of the aeolian formations in eastern Europe. Supposed sand provenance, dune orientation, and the few available datings suggest initial aeolian activity during cold stages of the Upper-Pleni (=full)glacial and Late Glacial, similar to northwest and central Europe. Dune formation was primarily supply controlled. Comparison of dune orientation with Late Glacial surface wind directions simulated by various GCMs permits reconstruction of dune activation with the positioning of (winter) westerlies over glacial deposits during the Oldest Dryas. Final widespread aeolian activity occurred during the Younger Dryas. As compared to the smaller fields toward the centre of deglaciation, aeolian sand deposits of the intermediate and periglacial zone benefited from distinctly longer intervals of accumulation. In the zone of deglaciation, aeolian activity was restricted to relatively isolated basins.

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By the end of the last glaciation, aeolian formations were either newly deposited or reactivated in periglacial Europe. Late Pleistocene aeolian sand deposits formed along the Weichselian (=Valdai=Vistulian) ice fronts in an almost continuous zone through northwest and central Europe. East of Poland (Fig. 1) the so-called 'sand belt' progresses with two separate arms into the Baltic Region and Belarus, respectively. Although its western portion includes a full glacial sand sheet, which covers and smoothens pre-existing topography (hence the term 'coversand'), inland dune fields account for the larger portion of the sand belt. The distribution of relic continental dunes has been described and related to the glacial topography by Högbom (1923), Markov (1928), Zemliakov (1928), Liedtke (1975), and Koster (1978), and for Poland by Nowaczyk (1986). These studies already suggest continuation of periglacial sand formations beyond the Polish border into the Baltic States, Belarus, and Ukraine. The earliest authors to recognize the extent of the sand belt to Niznij Novgorod (Russia) are Zemliakov (1928) and Cailleux (1969).

Periglacial aeolian formations are indicators of (glacial) sediment supply and provide information on palaeowind direction and soil moisture. Analyses of the sedimentological facies of coversand deposits (Ruegg 1983; Vandenberghe 1985; Schwan 1986, 1991; Kolstrup *et al.* 1990) and comparative studies in northwest Alaska and western Greenland (Koster & Dijkmans 1988; Dijkmans & Koster 1990; Dijkmans & Törnqvist 1991) provided an improved understanding of the cold-climate aeolian environment. Periglacial phenomena, such as pavement and cryogenetic structures, in addition to fossil fauna and botanical records (e.g. Kolstrup *et al.* 1990), contributed to reconstruction of a sparsely vegetated polar desert in Europe during the Pleni(=full) glacial (29 000 to 22 500 BP) and Upper-Pleniglacial (22 500 to some 14 000 BP). Trees and shrubs appeared in the landscape during the Bølling interstadial (13 000 to 12 000 BP) (Walker 1995). However, during the cold stages of the Late Glacial (13 000 to 10 000 BP) the periglacial climate and local drought once more favoured aeolian activity. Reactivation of local aeolian activity occurred sometime into the Holocene. At present, the aeolian landscape is predominantely occupied by pine trees and the (former) periglacial windblown sands have thus been immobilized, with the exception of a few spots of drift sands which were exposed by forest clearance, fire, overgrazing, ploughing, or episodic droughts (Koster 1978; Castel *et al.* 1989; Seppälä 1995).

The objective of the current research was to delimit the sand belt east of Poland, in the region affected by the Scandinavian glaciation, and to examine the nature of the aeolian deposit on a regional scale. The last Pleistocene glaciation supported three general aeolian environments in Europe: (1) the periglacial zone during maximum Weichselian ice extent (29 000 to 22 500 BP), (2) an intermediate zone of abandoned spillways and disconnected glacial features during ice retreat (18 000 to 13 000 BP), (3) a zone of deglaciation (13 000 to 9000 BP). Data were derived from various geologic and topographic maps of the Baltic States, Belarus, Ukraine and Russia (Zeeberg 1993, 1995). Lithostratigraphic descriptions of the aeolian formations in these districts are sparse and further explanation was obtained during field visits with local researchers. GCM simulations of Late Glacial and Younger Dryas surface winds (COHMAP Members 1988; Kutzbach *et al.* 1993; Isarin *et al.* 1997) and of (potential) aeolian sand drift (Blumberg & Greeley 1996) support interpretation of the observations.

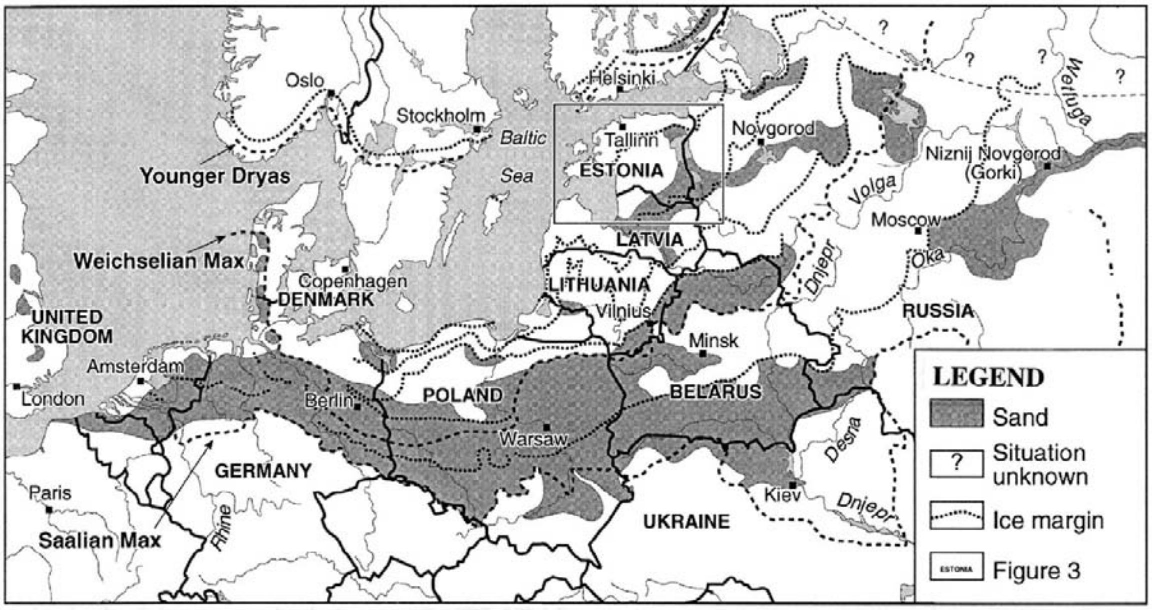

Fig. 1. Full extent of the European sand belt. For source references see caption to Fig. 3. The extent of the sand belt is shown in relation to ice-marginal lines of major glacial stages (hatches) and of substages (dotted). The current paper covers the region east of the Polish border. Dunes gradually disperse in a northeasterly direction.

Procedure

Dune fields encompass the majority of aeolian sand deposits in eastern Europe. Inland dunes, river dunes, drift-sand dunes and coversand ridges are morphogenetically all comparable and thus included in this inventory. Coastal dunes, active on the submergent coasts south of the present-day glacio-isostatic tilt line, are related to marine rather than glacial processes, and are for this reason omitted. In order to delimit the extent of the sand belt, relevant continental dunes have been plotted on a small scale topographic base map (Fig. 3). Aeolian landforms were traced on geological and geomorphological maps on scales of 1:200 000 to 1:500 000. Individual dunes were studied on 1:25 000 or 1:50 000 topographic maps and aerial photographs. This methodology enabled accurate plotting of dune fields. Points in Figs. 3 and 4 are of undefined size and merely locate dunes or dune fields in relation to glacial extent-limits (ice-border lines) and topography. Generally, the smallest feature indicated would be a single dune ridge of at least 3 m high.

The 1:25 000 and 1:50 000, and in some cases 1:200 000 scale maps allowed identification of the aeolian topography and its prevailing orientation. Parabolic dunes take shape according to factors such as: availability of sand, soil moisture, type and density of vegetation, and a unidirectional wind regime (David 1978, 1981; Dijkmans & Koster 1990; Pye & Tsoar 1990). Assuming that parabolic dune evolution occurs by blow-out migration, the long axis of parabolic dunes, or the line that bisects the angle of the converging dune arms, can be taken as pointing in the direction of the main dune-forming wind (cf. Galloway & Carter 1994). It should be noted that slip-face structures, rather than dune morphologies, would provide an accurate indication of transport directions and dominant winds. Dune orientations and geographical coordinates of major dune fields in eastern Europe are summarized in Table 1.

Stratigraphic framework

It is clear that 'aeolian phases' occurred in *northwest* and *central* Europe during the full glacial (29 000 to 22 500 BP) and Oldest Dryas (~14 000 to 13 000 BP), and within the Late Glacial during the Older Dryas (12 000 to 11 800 BP) and Younger Dryas (11 000 to 10 000 BP) (Koster 1988; explanation of chronozones in: Walker 1995). The dry climate and release of fine glacial sediments in proglacial regions contributed to a high 'aeolian effectiveness' during these cold stages. The aeolian sequence is relatively thin and often confined between a modern and Late Glacial boundary soil, pointing to few depositional events.

The lack of sufficient radiocarbon or thermoluminescence ages linked to dune deposits in eastern Europe leaves the synchronicity of events throughout Europe unclear. However, the architectural continuity

Table 1. Continental dunes in the Baltic States, Belarus, Ukraine and Russia.

Location	Coordinates	Orientation*	Age and strat**	Reference***
(Estonia)				
Iisaku	59°05′N 27°20′E	NW	4 (TL) – 11 ka/gl	Raukas *et al.* 1988
(Latvia)				
Gauja	57°40′N 26°00′E	WNW	< 10 300 yr/fl,gl	5–10
Pededze	57°05′N 27°00′E	WNW	< 11 ka/gl,fl	10–15
Daugava (W)	56°45′N 24°30′E	W	< 11 ka/gl,fl	9–17
Daugava (E)	56°10′N 26°20′E	WNW	13.5 ka/gl,fl	
(Lithuania)				
Nemunas	55°10′N 22°22′E	WSW	< 11 kg/fl,gl	10–20
Skersabalai	54°50′N 25°35′E	WSW	> 13.2 (TL) ka/gl	Satkunas *et al.* 1991
Dzukija	54°10′N 24°30′E	WSW	< 15 ka/gl	Gudelis & Vatoniené 1976
(Belarus)				
Zap. Dvina	55°35′N 29°00′E	WNW	gl,fl	5–12
Nemunas	53°45′N 26°20′E	WNW	gl,fl	
Sluč	52°35′N 27°30′E	WNW	gl,fl	6–12
Dnjepr	52°10′N 30°35′E	W	al,fl	
Gorin'	51°10′N 26°20′E	WNW	al	5–10
Ubort	51°20′N 28°20′E	W	al	8
(Ukraine)				
Pripyat	51°35′N 24°20′E	WNW	< 15 ka/al	2–10
Stochod	51°55′N 25°45′E	WNW	al	2–5
Už	51°15′N 29°35′E	WNW	al	5–12
Teterev	50°45′N 29°35′E	NW	al	5–20
(Russia)				
Novgorod	58°30′N 32°25′E	WNW	gl	
Suda	59°25′N 36°50′E	WNW	fl,gl	5–8
Oka (Pra)	54°50′N 40°20′E	W	< 15 ka/gl,al,fl	Drenova *et al.* 1997
Vjanka	55°05′N 41°50′E	W	< 15 ka/gl,al,fl	5–15
N. Novgorod	56°30′N 44°80′E	SW	al	Zemliakov 1928
Kil'mez	57°10′N 51°30′E	SW	al	2–15

* Wind direction acquired from dune orientation.
** Stratigraphic position, sand provenance: fl – fluviatile; al – alluvial (deflation of glaciofluvial, glacial and colluvial deposits); gl – glaciolacustrine and glaciofluvial outwash. Age approximated from available data.
*** Unreferenced sites: height from topographic map (m).

of sand belt deposits and available datings (Table 1) certainly suggest that similar climatic periods existed in northwest, central, and eastern Europe. A sample taken halfway down a Lithuanian dune yielded a thermoluminescence age of 13 200 BP (Satkunas *et al.* 1991). This sample points to initial dune activation connected with the termination of the full glacial. Radiocarbon dating of palaeosols southeast of Moscow (Fig. 2) demonstrated dune formation beginning in the Oldest Dryas (~ 14 000 BP to 13 000 BP) and continuing in the Older Dryas (12 000 to 11 800 BP) (Drenova *et al.* 1997). Fossil soils and organic horizons from the subsequent Alleröd interstadial (11 800 to 11 000 BP; cf. Walker 1995) have been used to date aeolian formations of the Younger Dryas between Britain and Poland (Koster 1988; Isarin et al. 1997). The Alleröd soil has never been associated with dunes in eastern Europe, but again this is probably due to lack of stratigraphic investigations. The closest reference is a site near the Ukrainian border dating a dune transgression on peatlands from the Alleröd (Buraczynski & Butrym 1989).

The relative age of aeolian features can be further separated according to sand provenance, because Late Glacial (and Preboreal) dune formation was governed by sand supply. Ice marginal deposits, bordering the maximum glacial extent-limit of a particular stage or regional advance, provided sources for aeolian reworking. Hence, projection of glacier margin positions (glacial extent-limits, ice-border lines, stationary lines) through the European sand belt (Figs. 3 and 4) supports a relative chronology of dune-forming events. Glacier margin positions include end moraines, marginal deposits, glacial relics, scouring surfaces, and glacial drainage.

The principal glacial stage boundaries (Fig. 3) which have been used for coarse subdivision of the sand belt are: Oka (correlated to Elsterian, Mindel), Dnjeper (Saalian, Riss) and Valdai (Weichselian, Vistulian, Würm). Note that in the old Russian stratigraphy the Oka stage is registered as an Early Pleistocene

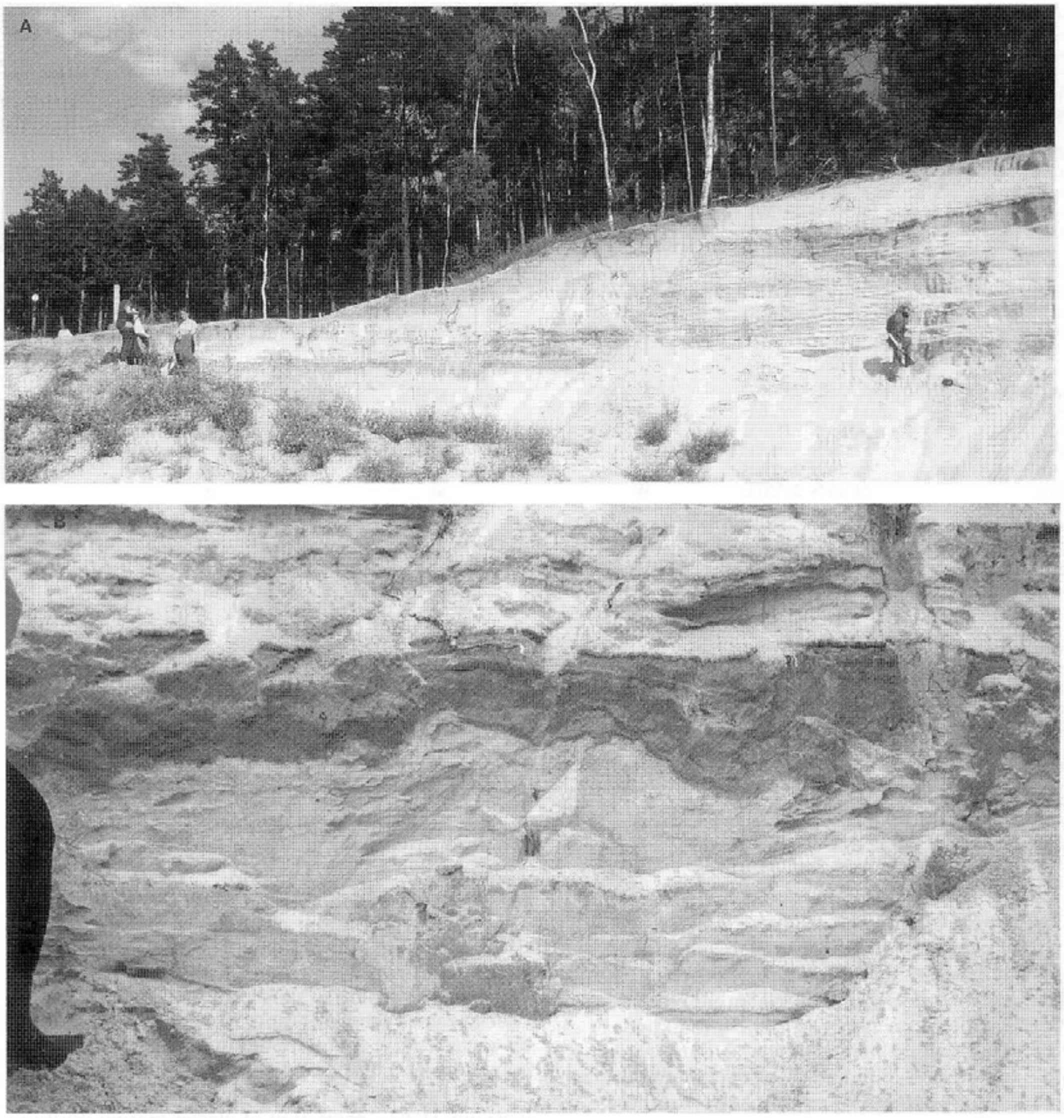

Fig. 2. □A. Section through a 4-m high dune ridge on an alluvial terrace of the Oka River, opposite the town of Kasjira (Russia, for location see Fig. 3). Figures stand at level of fossil soil. □B. Close-up of the cryoturbated Oldest Dryas soil (<0.5 m thick) that was used to date the beginning of aeolian activity in the area. Lower unit consists of horizontally laminated medium and fine-grained sands of the river terrace.

event, whereas the Elsterian is considered Middle Pleistocene in stratigraphies of Europe. The major stage of the Middle Pleistocene 'Dnjepr' glaciation, the Moscow stage, has been correlated to the Saalian 'Warthe' stage. In the Baltic region these stages are indicated by the following (Raukas & Gaigalas 1993): Lithuanian (Oka, Elsterian), Ugandi (Dnjepr, Saalian) and Nemunas (Valdai, Weichselian). Late Pleistocene (Weichselian) glacier flows and ice marginal environments on the east-European platform were described in greater detail by Kvasov (1979), Faustova (1984), Arkiphov *et al.* (1986), Velichko & Faustova (1986), and Faustova & Velichko (1992). Apart from the apparent name confusion, construction of an absolute stratigraphic framework for glacial stages and related aeolian action in Europe is complicated by the asynchroneity of local glacial activity.

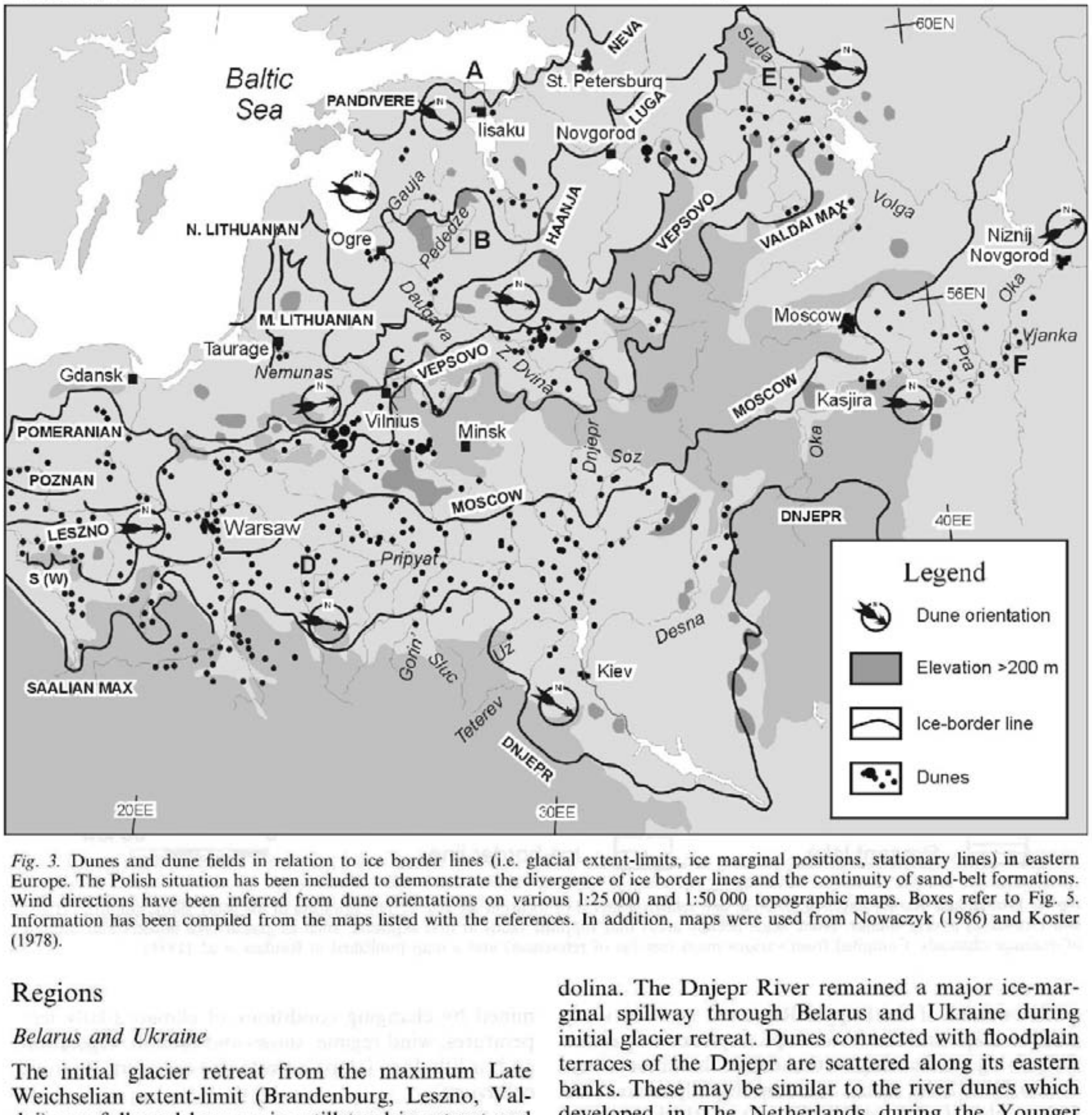

Fig. 3. Dunes and dune fields in relation to ice border lines (i.e. glacial extent-limits, ice marginal positions, stationary lines) in eastern Europe. The Polish situation has been included to demonstrate the divergence of ice border lines and the continuity of sand-belt formations. Wind directions have been inferred from dune orientations on various 1:25 000 and 1:50 000 topographic maps. Boxes refer to Fig. 5. Information has been compiled from the maps listed with the references. In addition, maps were used from Nowaczyk (1986) and Koster (1978).

Regions

Belarus and Ukraine

The initial glacier retreat from the maximum Late Weichselian extent-limit (Brandenburg, Leszno, Valdai) was followed by a major stillstand in retreat and re-advance to the Vepsovo (= Vepsa = Vepsian) limit, which occurred between 18 000 and 13 000 BP (Faustova 1984; Velichko & Faustova 1986). During the retreat, widespread aeolian activity occurred in abandoned spillway channels, particularly in the Pilica–Pripyat pradolina, Głogów–Baruth pradolina and Berlin–Warschaw pradolina. In Germany and Poland, dunes developed on, or downwind of alluvial fans, outwash fans (sandurs) and dry beddings (Richter *et al.* 1970; Liedtke 1975; Nowaczyk 1986; Kozarski & Nowaczyk 1991). This situation continued in the Belarussian part of the Pilica–Pripyat pradolina. The Dnjepr River remained a major ice-marginal spillway through Belarus and Ukraine during initial glacier retreat. Dunes connected with floodplain terraces of the Dnjepr are scattered along its eastern banks. These may be similar to the river dunes which developed in The Netherlands during the Younger Dryas (Koster 1988; Isarin *et al.* 1997). Dunes also appear where the Dnjepr and Soz Rivers cross the Moscow glacial extent-limit and cut into glaciofluvial deposits of Moscow age (Fig. 3), allowing a somewhat permanent deflation.

On the slopes of the Dnjepr (ice lobe)/Pripyat basin, especially the slope of the Ukrainian upland, long-lasting periglacial conditions controlled the growth of large parabolic dunes within the Dnjepr limit. Sands were most probably derived from periglacial slope deposits (colluvium). Dune ridges are widely spaced and extremely elongated (Fig. 5D). Along the south-

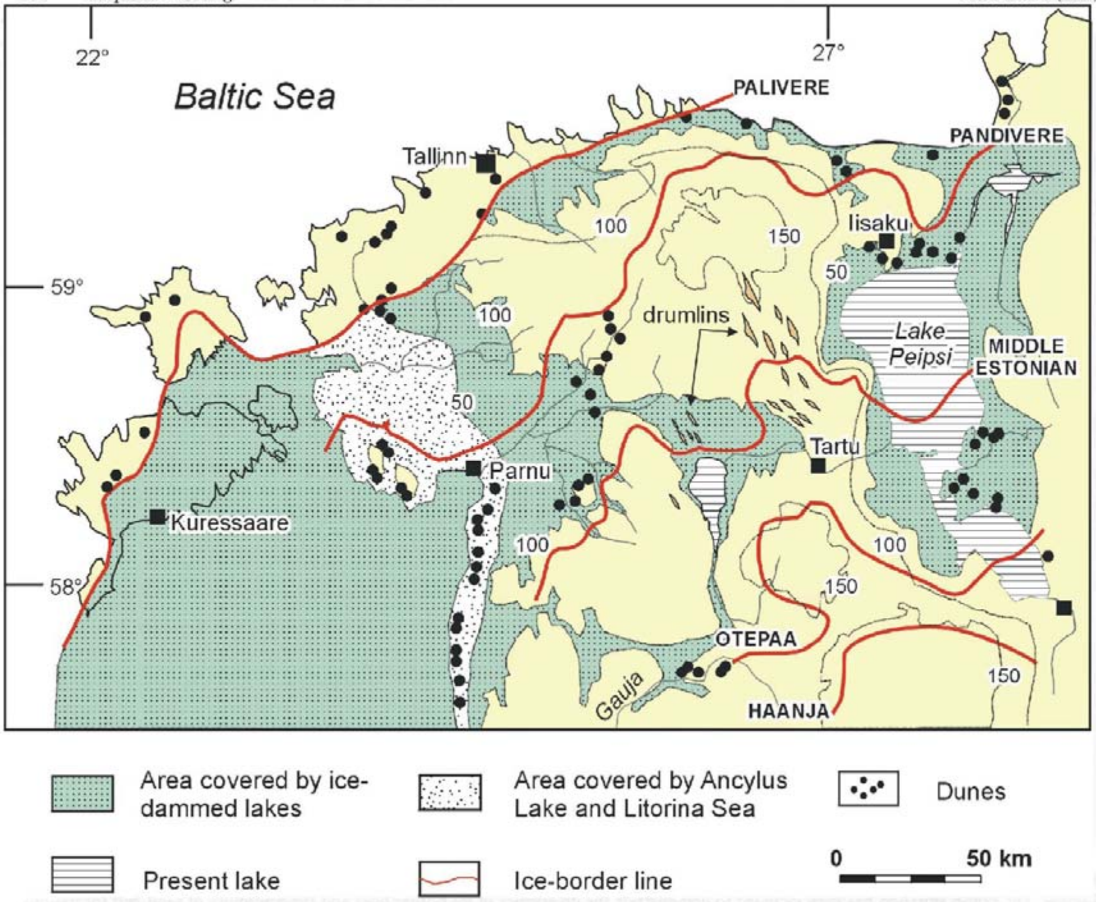

Fig. 4. Glacial and marine stages of Estonia, and related dunes. For location see Fig. 1. The situation in the other Baltic countries (Latvia and Lithuania) is very similar. Dune fields occupy areas that supplied sands at first exposure, such as glacial lake borders and beddings of drainage channels. Compiled from various maps (see list of references) and a map published in Raukas *et al.* (1971).

ern tributaries of the Pripyat River the 1:25 000 topographic maps show a downslope sequence of aeolian morphologies. Starting with aeolian hummocks upstream, parabolic dunes develop rapidly below the Dnjepr glacial extent-limit (Fig. 3). A thick cover of colluvium formed on the Polish side of the border during the cold stages of the full glacial. Dune sands cover peatlands formed during the Alleröd, demonstrating dune migration during the Younger Dryas (Buraczynski & Butrym 1989). The absence of organics inhibits construction of a chronostratigraphy. On the floodplain of the Pripyat River, dunes are buried by marshy 'limno-alluvial' (Russian map notation) sediments and, progressively in an easterly direction, only dune crests and caps emerge. The southernmost dunes of the European sand belt occur near the Ukranian Teterev River, a limit most probably determined by changing conditions of climate (daily temperatures, wind regime, snow- and rainfall, vegetation) and/or lithology (slope aspects and exposure, bedrock, colluvium).

Russia

East of the Central Russian Upland (Figs. 1 and 3) the sand belt continues along the Moscow glacial extent-limit (Middle Pleistocene *Glacial II-4*, Russian notation). Dune complexes developed on several glaciolacustrine terraces of the Oka River, southeast of Moscow, and farther east along the Oka and Volga Rivers. In the earliest publication on the dunes in this region, Zemliakov (1928) describes a meltwater-related dune complex on the 'left' (i.e. north/east) bank of the confluence of the Wetluga and Volga Rivers.

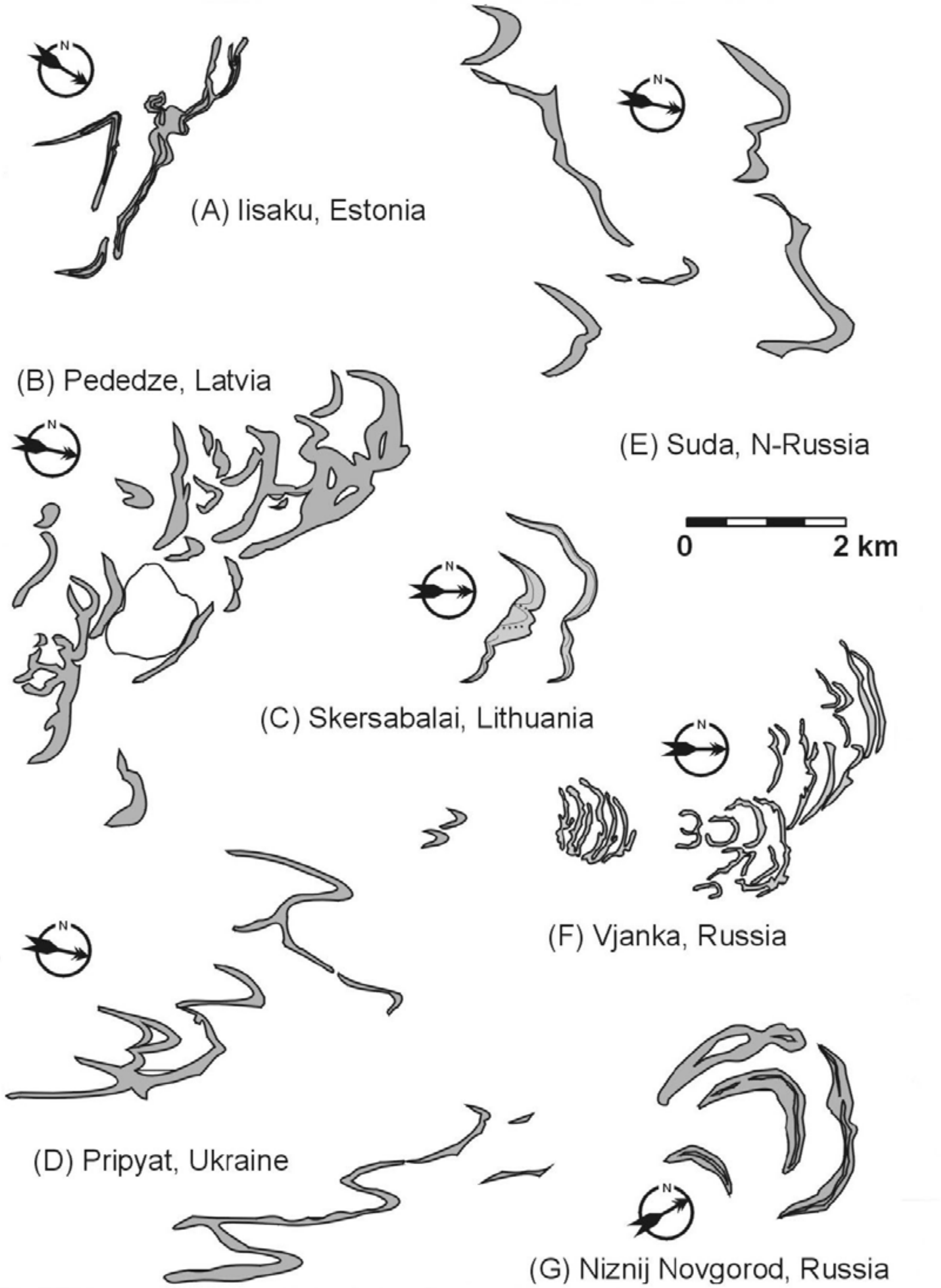

Fig. 5. Overview of dune outlines, and interpretation of dune-forming wind direction. For location see Fig. 3. Acquired from 1:25 000 and 1:50 000 scale topographic maps. All dunes are shown approximately on the same scale.

On the northern bank of the Oka River, opposite the town of Kasjira (Fig. 3), dunes transgress across several alluvial terraces. The dunes in this area average between 3 and 5 m in height but may reach as much as 20 m. Permafrost conditions are indicated by ice-wedge structures and cryoturbative distortions in buried soils underlying the aeolian sands (Fig. 2). Radiocarbon dating of these horizons yielded ages (Drenova *et al.* 1997) of 14 900 ± 780 BP (Oldest Dryas) and 12 680 ± 512 BP (Bølling). Thus, dune formation started in the Oldest Dryas, and continued in the Older and Younger Dryas.

Lithuania

The large Skersabalai and Dzukija dunefields in southeast Lithuania were first described by Kristapavičius (1960). North of Vilnius, glaciolacustrine sands were a source of the Skersabalai dune field (50 km^2). Dunes up to 15 m high (Fig. 5C) yielded thermoluminescence ages of 10 000 BP near the surface, to 13 200 BP halfway down the dune (Satkunas *et al.* 1991). Hence, dune formation started sometime before 13 200 BP and continued after 10 000 BP, i.e. into the Preboreal. The Dzukija Dune Field (900 km^2) accreted on outwash deposits in a large morainic depression parallel to marginal deposits (southwest–northeast). The erg displays a regular pattern of closely spaced dune ridges, some 30 m high and 4 km wide. Dune formation started in limited areas in the Oldest and Older Dryas (Gudelis & Vaitonienė 1976) and continued during the Younger Dryas. This is similar to the Oka dunes (Russia), which, by the division of the sand belt, appear to relate to an earlier glacial stage. The Dzukija and Skersabalai dunes, as compared to the smaller fields toward the centre of deglaciation, benefited from a distinctively longer period of formation and efficient growth during the cold stages. Southeast of Taurage separate dunes and a dune field of 20 km^2 can be found on glaciolacustrine sediments which were deposited by the Nemunas River in its ice lake. Aeolian reworking only commenced after drainage of this lake and emergence of the deposit.

North Latvia and Estonia

The deglaciation of the Baltic lowlands was completed by the end of the Younger Dryas (~10 000 BP). The ice margin was at Salpausselkä II in Finland and lower portions of Latvia and Estonia were still submerged (Fig. 4). Near Iisaku, north Estonia, an interesting and relatively well-developed continental dune field, measuring 50 km^2 at its main part, can be found predominantely downwind of a morainic ridge (and related glaciofluvial and glaciolacustrine deposits) of the Pandivere Stage (Raukas *et al.* 1971; Zeeberg 1993). The Pandivere (= Neva) re-advance in Estonia, dated to 12 700 BP (second half of the Bølling interstadial) is attributed to short cooling of the climate, or to surging of the glacier (Raukas & Gaigalas 1993). Kame plateaux, which formed in cracks of the dead ice (Raukas *et al.* 1971), show no signs of aeolian activity. Owing to the short-lived character of aeolian activity in this area, the transition of glaciolacustrine to aeolian sands has neither been distinguished in the sedimentological facies nor by grain analysis (cf. Mycielska-Dowgiallo 1993; Drenova *et al.* 1997). A series of thermoluminescence ages, obtained along a section through one of the dunes by Karukäpp yielded ages of 7100 to 4700 BP (Raukas *et al.* 1988), suggesting repeated reactivation during the Holocene. The field consists of slightly parabolic, roughly parallel ridges (Fig. 5A), and is located in the Lake Peipsi lowland, which remained flooded during various stages of ice lakes, ultimately merging into the Baltic Ice Lake (12 300 to 10 300 BP; Svensson 1991). In north Latvia, a group of inland dunes on both sides of the Gauja River appears to be related to drainage of the area and should therefore date younger than 10 300 BP (Table 1). Later lacustrine and marine stages of the Baltic Basin, i.e. the Ancylus Lake (9600 to 8000 BP; Svensson 1991) and Litorina Sea (8000 to some 7000 BP) left parallel ridges of shore-line derived dunes. These ridges are currently located in inland forests due to the postglacial land uplift (Fig. 6). Formation of glaciolacustrine basins, sandurs, and eskers continued until the final withdrawal of the ice in northern Scandinavia at around 8500 BP. Related deglacial dune formation finished in northern Sweden and Finland around 7000 BP (Seppälä 1972, 1995; Lindroos 1972).

Lithostratigraphic classification

Lithostratigraphic position

Factors controlling aeolian activity can be deduced by comparing dune formation in different regions or on different substrates. Discussion of these factors is beyond the scope of this paper. However, before any effect can be inferred, the lithostratigraphic position of a dune system or erg should be properly defined. From the current inventory it appears that all of the European continental dunes are located on, and sands derived from either alluvial/colluvial, floodplain, glaciofluvial, or glaciolacustrine surfaces. Accordingly, 'alluvial-derived dunes', 'fluvial-derived dunes', 'lacustrine-derived dunes', and 'shore-line derived dunes' have been categorized (Table 1).

Alluvial-derived dunes

To distinguish dunes connected with alluvial sources, the term 'alluvial-derived' is introduced for sandy deposits which were sorted out by wind from isolated river terraces (Fig. 2), abandoned spillways, and collu-

Fig. 6. Section through a shore-line-derived dune west of Tartu, central Estonia. Arrow indicates (westerly) dune-forming wind direction Note figures standing on lower scree; dune is approximately 8 m high. Dunes in eastern Europe are predominantly occupied by pine forest. The transition of pine forest on the well-drained dune ridges to peat bogs in wet interdune areas is often marked by a zone of birch trees.

vium. The classification of alluvial-derived dunes is based on 'unlimited' sand supply, i.e. not depending on instantaneous release or seasonal depositional events.

Fluvial-derived dunes

The term 'fluvial-derived' is reserved for dunes which form as a result of seasonal or periodic sand supply on floodplain terraces, river deltas and glaciofluvial outwash fans. River dunes, 'interbedded or reworked mixtures of fluvial and aeolian sediments' (Pye & Tsoar 1990; cf. Good & Bryant 1985; Dijkmans & Törnqvist 1991) are included within this class. Supply for fluvial-derived dunes is related to the activity of braided river systems which freeze in winter, thereby allowing deflation. Formation of Pleistocene river dunes ended when the character of the rivers changed (cf. van Huissteden & Vandenberghe 1988) from braiding to meandering with Preboreal climatic warming.

Lacustrine-derived dunes

'Lacustrine-derived' or 'lake-bottom dunes' formed where sand was derived from sand concentrations in ice-dammed lakes and glaciofluvial ponds. When these deposits drained, sudden exposure of the bottom sediments allowed high, instant sand supply. Glaciolacustrine and glaciofluvial sources both contributed to sand provenance for dunes in this group.

Shore-line derived dunes

Fossil dunes related to (peri)glacial lake shores (not to be mistaken with *coastal* dunes) have been distinguished in Estonia exclusively, but are likely to occur elsewhere. Formation of these 'shore-line derived dunes' is defined by short-term sand derivation from beach zones, before lake drainage or shore displacement and resulting dune isolation occur. Dune ridges are transversal, with little or no migration after formation (Fig. 6).

Glacio-aeolian zonation

Northwest European sand sheet vs. east European dunes

Ice-border lines, representing glacier margin positions (glacial extent-limits) mark the boundaries of three aeolian environments in Europe: (1) the periglacial zone during maximum Weichselian ice extent (29 000 to 22 500 BP), (2) an intermediate zone of abandoned spillways and disconnected glacial features during ice retreat (18 000 to 13 000 BP), (3) a zone of deglaciation (13 000 to some 9000 BP). The transition of sand sheets to dunes, and variation in the outlines of the parabolic dunes (Fig. 5), are proposed to have resulted from this zonation.

Coversand (considered a sand sheet) is likely to be common in the (periglacial) aeolian zone of eastern Europe. Coversand, in The Netherlands a 5- to 10-m thick, horizontally laminated deposit (Ruegg 1983), resulted from net sand deposition at a relatively slow rate (Schwan 1986, 1991; Pyritz 1972). Studies in Greenland confirm that a limited but steady supply of sand may account for the building of a cold-climate sand sheet (Dijkmans & Törnqvist 1991). Coversand has been studied in The Netherlands and in Denmark (Kolstrup et al. 1990) in considerable detail. An important difference between dunes and coversand is their time of formation. Redeposition and sorting of fine sands by full glacial aeolian action took place between 29 000 and some 22 500 BP (Koster 1988). The Older and Younger Dryas, the dune-forming periods of the Late Glacial, lasted less than a 1000 years each. In contrast to the coversand deposit, dune fields are closely related to ice-marginal deposits and short-lived meltwater environments. Thus, whereas dune formation appears to be primarily supply controlled, variations in deposition during sand-sheet formation (possibly including dune formation) may have been climate driven.

In northwest Europe, sea level lowering had exposed large portions of the North Sea shelf and full glacial sand derivation is commonly related to deflation of this area. General circulation models, however, indicate the presence of a large glacial high throughout the year (Kutzbach et al. 1993, Harrison et al. 1996). The anticyclone accounted for eastern airflow during the full glacial and would have restricted sand transport in a western direction. Furthermore, tundra covered the area and limited widespread sand transport. A more likely full glacial sand source is in-situ weathering and deflation of alluvium, possibly related to glacial deposits from the Saalian glaciation. The anticyclone blocked moisture supply and prolonged drought conditions during the full glacial may have stimulated the growth of extensive coversand bodies.

Dune formation and deglaciation

In the deglaciated area (north of the Pomeranian/Vepsovo line) dunes are of much younger age than in the other two zones and should date to the very end of the Late Glacial. Reworking of sediments was limited to relatively isolated basins (i.e. glacial lake bottoms), resulting in compressed, nested fields and almost transversal ridges. Dry sand became available for aeolian redistribution only after (ground) water levels had lowered and soils dried, a process that was accelerated by postglacial land uplift, drainage of ice-dammed lakes, and lowering of the permafrost table. As soon as the water level of ice-dammed lakes in Lithuania and Latvia dropped, dunes started to develop on the exposed borders. As glacier retreat progressed and ice-dammed lakes drained, glaciolacustrine plains connected with Middle Lithuanian and North Lithuanian (Luga) glacier margin positions emerged throughout Latvia. Perpendicular to the Daugava River is a long and narrow dune field, which is embayed by moraine at its higher end, while the lower portion is situated in more open topography. The higher end became completely developed, but only a few separate dune ridges developed in its lowland parts, suggesting a later formation, when water levels had further lowered. On a plain drained by the Pededze River in north Latvia, straight parabolic, almost transversal dune ridges curve eastward around a small lake (Fig. 5B). The suggestion that a dead-ice block may have caused this deflection supports the theory of dune development immediately following deglaciation, when ground ice was still present. An indication that dune migration in this area occurred during winter comes from the description of a small dune field in west Latvia, which has been dissected by the melting of a frozen stream (Eberhards, pers. comm. 1993).

Dune orientation and atmospheric circulation

General circulation models

Palaeoclimatic interpretation of the encountered dune orientations is restricted because of lack of stratigraphic data. Observations in Alaska (Galloway & Carter 1993) and Greenland (Dijkmans & Törnqvist 1991) imply that dunes reflect the dominant directional wind regime of the climatic episode that favoured deflation. Sand transport occurs by winds exceeding the threshold velocity of a particular grain size (Bagnold 1941; Greeley & Iversen 1985; Pye & Tsoar 1990). The resultant sand drift can be simulated by general circulation models (Blumberg & Greeley 1996). At the spatial scale of current GCMs, aeolian features effectively record the dominant atmospheric circulation, masking short-term variations in climate (Blumberg & Greeley 1996). Since no studies are known to exist of the palaeoclimatic signature of European continental dunes, interpretation of dune orientation with respect to regional circulation and climatic change rests solely on GCM simulations.

The overall westerly orientation (and local northern/southern deviation) of parabolic dunes in Europe (Figs. 3 and 5) qualitatively supports the reconstruction of 12 000 BP January surface winds by the COHMAP global circulation model (COHMAP Members 1988; Kutzbach *et al.* 1993). Reconstructions obtained for 15 000 BP are almost identical to those for 18 000 BP, but by 12 000 BP the experiments point toward significant changes in flow patterns (Kutzbach *et al.* 1993; Kutzbach & Webb 1993). The 12 000 BP 'snapshot' is considered a representative window for the Late Glacial (Kutzbach *et al.* 1993). Simulation of Late Glacial wind speeds and direction for selected cells over The Netherlands and Poland (Isarin *et al.* 1997) is in general agreement with the COHMAP results.

Discussion

The outcome and conceptual background of the GCMs (Kutzbach & Webb 1993; Harrison *et al.* 1992) provide clues to the question why dune formation appears to be restricted to the Late Glacial. No dunes are known from the Upper-Pleni(full) glacial (22 500 to 14 000 BP), when a cold and dry climate, sparse steppe/tundra vegetation, and release of fine glacial sediments in proglacial regions would also have allowed dune formation. Hence, there was either a lack of sufficiently strong unidirectional winds, or Late Glacial aeolian action has eroded or buried these features.

Until 15 000 BP, the European climate was dominated by a large glacial high centred over the northern Atlantic, and a large high over Eurasia. The anticyclonic circulation enhanced the continental climate and as a result glaciers became thinner and less productive in an easterly direction (Faustova 1984). The easterly flow may thus account for the decreasing density of aeolian formations in a northeasterly direction. As the ice cap retreated and lowered, non-glacial circulation and supply of precipitation gradually returned. Permafrost features show that between 16 000 and 15 000 BP a cold climate in eastern Europe existed simultaneously with non-permafrost conditions in northwest Europe (Böse 1991). The effect of the glacial anti-cyclone further diminished and an easterly flow, as suggested to have existed during the Late Glacial by Harrison *et al.* (1996), would have been restricted to southern Scandinavia. The COHMAP reconstruction for January 12 000 BP accounts for anomalous surface pressure associated with the remaining ice sheet.

With the onset of the Oldest Dryas cold stage (~14 000 BP), conditions were optimal for aeolian sand transport. The simultaneous timing of dune formation at this point throughout Europe implies the effect of a continent-scale climatic force. It is likely that dune formation was initiated by the location of a mid-latitude high-pressure cell in January over southwest Europe, together with the development of the Icelandic low. The resulting pressure gradient caused a strong unidirectional flow from the Atlantic into northwest Europe during the winter months (Kutzbach *et al.* 1993). GCM simulations show that during the Younger Dryas highest wind speeds were achieved from September through May (Isarin *et al.* 1997). A similar aeolian season still exists in modern periglacial environments. Dune migration was apparently less significant for the rest of the year, when winds were more variable and not as strong. Winter transport would occur with incorporation of snow in the aeolian formations, resulting in denivation melt structures in the following melting season. The preservation potential of niveo-aeolian deposition is generally low, but best under a unimodal wind regime and/or with high migration rates (Koster & Dijkmans 1988). Sedimentological studies of the dunes should therefore reveal denivation features.

Late Glacial dunes may lastly and finally have been activated by Younger Dryas winds. However, the dune-forming process in the deglaciating region, beginning toward the end of the Younger Dryas, was short-lived due to rapid climatic amelioration. Owing to orbital changes (axial tilt, perihelion), the seasonality of the climate in the Northern Hemisphere increased during the Late Glacial, reaching a maximum around 9000 BP. The warmer summer temperatures and a moister climate allowed rapid invasion of shrubs and trees, preventing extensive aeolian action in Latvia and Estonia. A rise of the water table under humid Holocene conditions initiated extensive peat formation and stabilized aeolian landforms.

Conclusions

Aeolian sand deposits form a continuous belt through northwest, central and eastern Europe. Dune fields occur on alluvial/colluvial, floodplain, glaciofluvial, or glaciolacustrine surfaces. Sands were most likely derived by in situ aeolian reworking, demonstrating limited sand transport. There is a distinct lack of detailed lithostratigraphic description of aeolian sands in eastern Europe.

The last Pleistocene glaciation supported three general aeolian environments in Europe. South of the Vepsovo glacial extent-line, continental dune building started throughout eastern Europe during the Oldest Dryas (~14 000 to 13 000 BP). Dune formation continued during the cold stages of the Late Glacial. North of the Vepsovo line, in the deglaciating zone, dune formation continued through the Preboreal and Boreal until around 8000 BP. Long-lasting periglacial conditions, stimulated by the presence of a glacial anticyclone during the full glacial may have allowed accumulation of coversands in the outermost glacio-aeolian zone.

Dune formation appears to be primarily controlled by sand supply in ice-marginal environments. Dune orientations qualitatively support GCM reconstructions of surface winds, suggesting that Late Glacial dune building (and migration) was initiated and governed by positioning of strong unidirectional westerlies over the periglacial region during the winter season.

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