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# Development of plateau dunes controlled by iron pan formation and changes in land use and climate

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ABSTRACT

Plateau dunes are unique landforms which formed as erosion relicts in blow-out areas in Late Pleistocene sandy deposits. They are negative forms in contrast to normal dunes where sand is accumulated (positive form). Plateau dunes are located in the European Aeolian Sand Belt in the Netherlands, Germany and Denmark and they are flat-topped features with a bog in the central part often covered by a thin aeolian sand layer. A conceptual model of formation and further development of plateau dunes in time are presented in detail, using $^{14}C$ dates of buried peat layers and OSL dates of sandy sediments. Special focus is on the influence of climate factors, pedology, and human activity on the formation of plateau dunes.

## 1. Introduction

Many landscapes in Denmark are shaped by the wind, e.g. the coastal dune landscape along the west coast and large areas of shifting sand further inland. Inland dunes are generally much older than the coastal dunes and shaped during periods of sparse vegetation. The oldest inland dunes and aeolian cover sands are from the Late Weichselian or Early Holocene. Later in the Stone and Bronze Ages and especially the Iron Age, aeolian landscapes also developed when cultivation and removal of vegetation covers had opened up the landscape (Rasmussen, 2005; Rasmussen and Bradshaw, 2005). In historical times, Denmark deforested during the Little Ice Age in 1250–1850, and in the 17th century, forests covered < 1% of the country. Several villages were abandoned as they were invaded by large inland dunes. Some appear as orderly parabolic or sickle-shaped dunes; others as slightly undulating cover sands. The source of the dune sand is neighboring areas in which deflation surfaces formed. These surfaces now remained coarse sandy or gravelly as the wind has not been able to transport such grain sizes. On very few of these surfaces, erosion remnants of the original landscape appear as low flat "islands" rising over the deflation plain. These are termed the plateau dunes (Fig. 1).

Plateau dunes are characterized by their genesis and shape. They are genetically erosion relics forming "islands" in a rather flat deflation landscape. They can be taller than 4 m and bordered by steep slopes. The top part of the bigger plateau dunes is rather flat with a low sandy rim and a shallow wet central depression; occasionally a free perched water table is present. The natural vegetation mirrors the wetness with grasses and common heather (*Calluna vulgaris)* on the dry rim and cotton grass (*Eriophorum vaginatum)* and bell heather (*Erica tetralix)* in the depression. The bigger plateau dunes of up to about 5 ha are characterized by a buried soil profile, normally a podzol according to World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). The podzol B-horizon is rather impermeable because of enrichment with iron and aluminum and especially the formation of impermeable placic horizons; therefore, peaty layers up to about one and a half meters in thickness formed above the podzol. The peat layers are important for the formation of the plateau dunes because the surface of the peat is stable. It protects the plateau dune from deflation as occurred in its surroundings. Blow-out sand from the surroundings can accumulate on these wet peat surfaces. In the small plateau dunes, the peat layer is thin and often not > 20 cm thick; there is no rim or a central depression but the top has a convex shape with maximum aeolian sand deposited in the central part.

The plateau dunes are unique landforms described on the European Aeolian Sand Belt in the Netherlands, Germany and Denmark. They are present in Saale glaciation landscapes and on outwash plains from Weichsel (Koster, 2005; Koster, 2009; Tolksdorf and Kaiser, 2012). Previously, plateau dunes received relatively little attention in the

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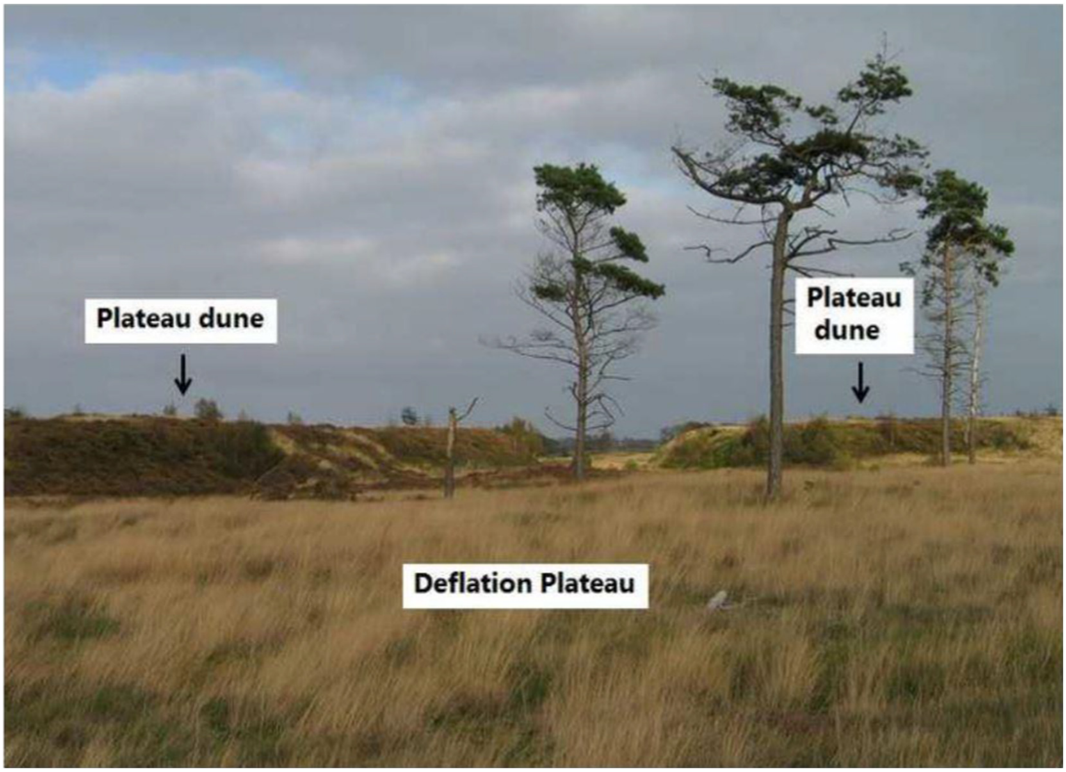


**Fig. 1.** A typical plateau dune from the Stensbæk research area.

scientific literature. In the Netherlands, Polak (1968), Koster (1970, 1978) and Castel (1991) investigated peat layers in plateau dunes in Veluwe and Drenthe. Through pollen and $^{14}C$ analyses, they found that the peat formation ended 700–900 years ago; the drift of sand taking place at some point thereafter. In Germany, Solger (1910) described plateau dunes, and Sørensen (1939, 1972), Hansen (1966), Stenz and Sørensen (1969) and Breuning-Madsen et al. (2013) described plateau dunes from Denmark. In the Frøslev Plantation, the age of the peat in a plateau dune was determined through $^{14}C$ analysis to be about 850 years old (Sørensen, 1972).

The dating of the plateau dunes was previously limited to $^{14}C$ dating of the peat layer in the dunes, and it was therefore impossible to date the different phases of development. The introduction of OSL dating enabled dating of the deposition of both aeolian and alluvial sand. It is now possible to date the complete development of the plateau dunes by combining AMS $^{14}C$ and OSL dating.

In this study, we show, based on studies of landscape morphology, soil profile development, chemical and physical soil analyses, and through dating using AMS $^{14}C$ and OSL methodologies, that the formation of a plateau dune landscape is due to a combined effect of pedology, land use and climate.

## 2. Study site

We investigated the plateau dune landscape in the Stensbæk Plantation in Southern Jutland, Denmark (Fig. 2). It is located on a narrow outwash plain between two Saale glaciation landscapes. For a short period after the Ice Age, the natural vegetation was birch and pine followed by several thousand years of deciduous forest (oak, lime ash and hazel). Beech became the dominant tree in Denmark about 2500 BP due to climate change, and in sandy areas, heather became common (Iversen, 1973). Over the past 6000 years, human activity has turned part of the land into farmland (Aaby, 1986). The study site has a humid temperate climate. The average temperature in the warmest month July is about 16 °C and in the coldest month January it is about 0 °C. The average yearly precipitation is app. 750 mm (DMI, 2017).

Fig. 3 shows a topographic map (LIDAR based digital elevation model) from the Danish Geodata Agency, (2015). The wind has blown away large volumes of sand and the surface level fell several meters forming a deflation plateau at about 14.5 m above sea level. On the plateau, > 10 well-developed plateau dunes exist (Fig. 3). The well-developed plateau dunes rise about 3–5 m above the blow-off or deflation area, and their top level is almost the same as that of the outwash plain towards the west. Today the vegetation is mainly heather, but in former times, forests and agriculture probably existed. East of the plateau dune area towards the river, a dune rim is seen (Fig. 3). Drift sand from in-between the plateau dunes have probably built up the rim.

## 3. Field work

All potential plateau dunes recognized on the elevation model (LIDAR) were verified in the field. The plateau dunes with steep slopes and a leveled top plateau were selected to perform auger drilling. The drilling was carried out using hand-driven chamber augers for sandy or stony soils, and the deepest borehole was about 4 m. In the central wet part of the plateau dunes, a casing was used below the groundwater level to prevent saturated sand from flowing into the borehole.

Based on the survey, two plateau dunes were selected to determine the formation of the plateau dunes in detail. One of the two plateau dunes studied was a three and a half meter high plateau dune through which a transect was excavated for a path construction (Fig. 3, letter A). This has partly drained the plateau dune and made it suitable for making a 2 m wide cut to the base (outwash plain) through its central part. The plateau dune was not the wettest of the plateau dunes, but even so it took some days before the water had stopped running into the cut. In this cut, it was possible to follow the outline of the placic horizons being the precondition for the development of peat layers (Sørensen, 1972). Furthermore, it was possible to make the OSL sampling by hammering 25 cm long metal tubes with a diameter of 2 cm into the profile wall. The OSL sampling strategy was to date the sandy