



## Holocene palaeosols and aeolian activities in the Umimmalissuaq valley, West Greenland

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## Holocene palaeosols and aeolian activities in the Ummimalissuaq valley, West Greenland

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| Keywords:                     | Palaeosols, aeolian transport, grain size analysis, AMS radiocarbon dating, deglaciation, Greenland, OSL dating  |
| Abstract:                     | <p>Aeolian sand sheets and active dunefields preserve an ancient Holocene land surface represented by palaeosols that occur around the present ice margin in the Kangerlussuaq area, West Greenland. To determine the relation between Holocene aeolian activities and periods of soil formation, both substantially dependent on the deglaciation history, palaeosols, aeolian sand sheets, and dunefields were analysed using field data, grain size analyses, optically stimulated luminescence dating and AMS <math>^{14}\text{C}</math> data in an area of about 15 km<sup>2</sup> of the Ummimalissuaq valley. Located under dunefields close to the ice margin (&lt; 2 km), palaeosols are developed in fine-grained aeolian sediment (silt loam) and covered by sandy aeolian layers. Silt contents of palaeosols of partly &gt; 60 wt.% are comparable to aeolian sand sheets currently formed at further distances (4-5 km) from the present ice margin. We propose a transport distance of fine aeolian sediments, in which the palaeosols are formed, of at least 4 kilometres from inboard of the present ice margin. Soil formation of the palaeosols started around 2700 cal yr b2k. Datings from the youngest parts of the palaeosols suggest a stable period of around 2400 years, which allowed for pedogenesis and was characterised by low but constant aeolian activity. Since aeolian activity intensified after around 300 cal yr b2k and developed still active dunefields with coarse and medium sand accumulation, the ice margin must have reached its present position since then.</p> |

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3 **Holocene palaeosols and aeolian activities in the Umimmalissuaq valley, West**  
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3 20 **Abstract**  
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5 Aeolian sand sheets and active dunefields preserve an ancient Holocene land surface  
6 represented by palaeosols that occur around the present ice margin in the Kangerlussuaq area,  
7 West Greenland. To determine the relation between Holocene aeolian activities and periods of  
8 soil formation, both substantially dependent on the deglaciation history, palaeosols, aeolian  
9 sand sheets, and dunefields were analysed using field data, grain size analyses, optically  
10 stimulated luminescence dating and AMS <sup>14</sup>C data in an area of about 15 km<sup>2</sup> of the  
11 Ummimalissuaq valley. Located under dunefields close to the ice margin (< 2 km), palaeosols  
12 are developed in fine-grained aeolian sediment (silt loam) and covered by sandy aeolian  
13 layers. Silt contents of palaeosols of partly > 60 wt.% are comparable to aeolian sand sheets  
14 currently formed at further distances (4-5 km) from the present ice margin. We propose a  
15 transport distance of fine aeolian sediments, in which the palaeosols are formed, of at least 4  
16 kilometres from inboard of the present ice margin. Soil formation of the palaeosols started  
17 around 2700 cal yr b2k. Datings from the youngest parts of the palaeosols suggest a stable  
18 period of around 2400 years, which allowed for pedogenesis and was characterised by low but  
19 constant aeolian activity. Since aeolian activity intensified after around 300 cal yr b2k and  
20 developed still active dunefields with coarse and medium sand accumulation, the ice margin  
21 must have reached its present position since then.  
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45 **Keywords**

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47 40 Palaeosols, aeolian transport, grain size analysis, AMS radiocarbon dating, OSL dating,  
48 deglaciation, Greenland  
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## Introduction

In general, areas close to the margins of ice sheets are strongly affected by aeolian activity (e.g. Dijkmans and Törnqvist, 1991; Willemse et al., 2003; French, 2007; Brookfield, 2011).

45 This is mainly due to strong katabatic winds associated with steep pressure gradients that develop at the margins of ice sheets (Schaetzl and Loope, 2008; Brookfield, 2011), where they reach their highest speeds (Dijkmans and Törnqvist, 1991).

The driving controls on most aeolian systems and particularly on sand sheet environments like in West Greenland are the source area, the availability of the source material, and wind speed. The outwash-source zone for aeolian sand and silt is commonly controlled by variable discharge. In general, meltwater valleys near the margins of ice sheets are filled with silt-rich discharge in summer, and become dry and unprotected to aeolian erosion predominantly in winter (Schaetzl and Loope, 2008). Also, during winter with saltating snow and ice, aeolian mobility of sand is enhanced. The formation of a sand sheet either reflects adhesion to a wetted surface or with vegetation (e.g. Koster and Dijkmans, 1988; Ruz and Allard, 1995). Often, the presence of snow and interstitial ice binds aeolian particles to surfaces necessitating higher threshold shear velocities for transport (Ollerhead et al., 2013), though the sublimation rate may be an important factor in grain release (Van Dijk and Law, 1995). The presence of snow ramparts and interstitial layers mostly composed of snow can enhance aeolian accretion and dune movement (Koster and Dijkmans, 1988; Dijkmans and Mùcher, 1989; Ruz and Allard, 1995). Further, aeolian transport and deposition of sand and silt is suggested to be affected and limited by topographical barriers (e.g. Mason et al., 1999; Mason, 2001).

Previous studies have shown a correlation between the distribution of wind-blown sediments and grain size, and the former extent of the ice sheet in West Greenland (e.g. Scholz and Grottenthaler, 1988; Dijkmans and Törnqvist, 1991; Willemse et al., 2003). Driven by Holocene climatic fluctuations alternating phases of both soil formation and aeolian activity occurred with different intensities (e.g. Ståblein, 1975; Ten Brink, 1975; Weidick, 1985;

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3 Scholz and Grottenthaler, 1988; Dijkmans and Törnqvist, 1991; Van Tatenhove et al., 1996;  
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5 Ozols, 2003; Willemse et al., 2003; Forman et al., 2007). The forefield of the inland ice  
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7 margin was affected by permanent modifications of the palaeoenvironment due to changing  
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9 glacial dynamics, and alternating glaciofluvial and aeolian processes. These processes may be  
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11 linked in complex manners; however the intensity of glaciofluvial and aeolian processes  
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13 decreases with increasing distance from the ice margin (Dijkmans and Törnqvist, 1991;  
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15 Schaetzl and Loope, 2008), and correspondingly the influence of wind on erosion and  
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17 sedimentation. Therefore, the changing distance from the ice margin to the outwash-source  
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19 zone affected the variability in discharge, and thus the supply of aeolian sand and silt, which  
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21 had impacts on the formation of soils, aeolian sand sheets and dunefields in the Holocene (cf.  
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23 Willemse et al., 2003). Palaeosols developed in the aeolian sediments around Kangerlussuaq  
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25 indicate an interruption or decrease of aeolian activity (e.g. Scholz and Grottenthaler, 1988;  
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27 Dijkmans and Törnqvist, 1991; Willemse et al., 2003). They can be taken as proxies for stable  
28  
29 environmental conditions. For the timing of soil formation different data exist. According to  
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31 Van Tatenhove et al. (1996) soil formation in Sandflugtdalen (Figure 1a) north of the study  
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33 area started around 4560 cal yr b2k. Willemse et al. (2003) assume an onset of soil formation  
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35 prior to 3450 cal yr b2k and a halt in soil formation 600 cal yr b2k in Sandflugtdalen and  
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37 Ørkendalen (Figure 1a). Similarly, Dijkmans and Törnqvist (1991) suggest soil formation  
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39 between 3350 cal yr b2k and 650 cal yr b2k. Likewise, Forman et al. (2007) propose the  
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41 beginning of soil formation after 3 ka, whereas Ozols (2003, 1600 cal yr b2k) and Scholz and  
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43 Grottenthaler (1988, 1.5 ka) assume a distinct later start. In general, soil formation around  
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45 Kangerlussuaq has been strongly connected to dynamics of the inland ice: During a retreat of  
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47 ice, changing environmental conditions favoured soil formation in the study area due to lower  
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49 discharge or more distal location from the source area, and thus lower intensity of katabatic  
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51 winds and less supply of aeolian, whereas an advance led to an interruption of soil formation  
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3 caused by opposite conditions. However, knowledge regarding the exact timing of soil  
4 formation in the Kangerlussuaq area is still insufficient, and more data are needed.  
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7 95 In this study, we aim to characterise the results of interaction of both aeolian-geomorphic  
8 processes and pedogenic processes across an E-W oriented valley in West Greenland. We  
9 further aim to understand how the intensity of these processes changed in response to middle  
10 and late Holocene glacial retreat and readvance. The lines of evidence include 1) the spatial  
11 patterns of modern landforms, surface sediments, and soils, and 2) the stratigraphy observed  
12 along sampling transects, which allows for temporal reconstruction of these spatial patterns.  
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### 20 21 22 23 **Study area**

24 The Kangerlussuaq area is characterised by an E-W and ENE-WSW oriented valley system  
25 that leads the meltwater to the sea (Scholz and Grottenthaler, 1988). The E-W oriented  
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29 105 Umimmalissuaq valley is located in West Greenland, around 30 kilometres southeast of  
30 Kangerlussuaq (Figures 1a, b).  
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36 Figure 1. (a) (b)  
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41 110 The bedrock in the study area is mainly Precambrian gneiss (e.g. Scholz and Grottenthaler,  
42 1988; Ozols and Broll, 2003; Henriksen, 2008); therefore the aeolian transported material  
43 consists of non-calcareous and non-basaltic material. Based on own field observations, the  
44 Ørkendalen glacier (Figure 1b) at the eastern side of the study area forms an active moraine  
45 system, which is overrunning current vegetation (Figure 2a). We observed the meltwater to  
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52 115 drain predominantly northward in the Ørkendalen valley, but also in the direction of the  
53 Umimmalissuaq valley. Forming a glacial outwash plain or sandur, and a delta, meltwater  
54 drains more or less directly into a lake system towards southwest and west, not using the  
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3 outwash plain is small (ca. 0.2 km<sup>2</sup>). The entire outwash plain generally acts as source for  
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5 120 aeolian sediments. Own field observations indicated aeolian sand and silt to be mainly blown  
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7 out from northwestern parts of the outwash plain (ca. 200-300 m southeast of profile D1, cf.  
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9 Figure 1b), which are barely affected by meltwater channels in summer. Most parts of the  
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11 valley itself are higher in elevation than the outwash plain (up to 50 m). The study area further  
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13 includes the hills north and south of the valley, which rise up to 150 m higher than the  
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16 125 outwash plain (Figures 1b, 2b).

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18 The valley is covered by glacial deposits of the Keglen and Ørkendalen moraine systems as a  
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20 result of the middle and late Holocene re-advances of the ice sheet (Stäblein, 1975; Ten  
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22 Brink, 1975; Weidick, 1985). Moreover, glaciofluvial sediments are widespread in the valley.  
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24 The glacial and glaciofluvial deposits, and most of the valley bottom and slopes are covered  
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27 130 by a fine-grained aeolian sand sheet (ca. 60% coverage, Figure 1b), apart from areas close to  
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29 the ice margin (sandur, recent moraine, dunefields). North, northwest and west of the glacial  
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31 outwash plain, there are still active coarse-grained dunefields (ca. 5 % coverage; Figures 1b,  
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33 2b-d). Numerous distinct deflation areas cut into the aeolian sand sheet, and are present  
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35 predominantly on top of moraines and slopes facing the ice margin (Figure 1b).

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40 Figure 2. (a) (b) (c) (d)

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45 The weather station closest to the study area is Kangerlussuaq Airport (Figure 1a). The  
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47 present-day climate of Kangerlussuaq is Low Arctic continental: mean annual air temperature  
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49 140 is -4.8°C and mean annual precipitation is 257 mm (1979-2008; according to data from Boas  
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51 and Wang, 2011). Low precipitation in winter (Cappelen, 2001) indicates a thin snow cover in  
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53 the study area during winter months (Ozols and Broll, 2003). In Kangerlussuaq, mean wind  
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55 speed at 2 m above ground level is 3.6 m/s (1985-1999; Cappelen, 2001). Mean maximum  
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57 wind speed at the same height is 19.6 m/s (1985-1999; Cappelen, 2001), and most frequent  
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3 145 wind direction is NE (Cappelen, 2001), indicating the effect of thermally induced katabatic  
4 winds and airflow channelling in the valleys (Van den Broeke and Gallée, 1996). The  
5 Umimmalissuaq valley is strongly affected by these katabatic winds which are stronger in  
6 winter due to a negative surface radiation and therefore a temperature deficiency above the  
7 snow-covered ablation zone (Willemse, 2000). Compared to Kangerlussuaq, the study area is  
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14 150 linked directly to the inland ice (Figures 1a, b). Thus, it is most probably drier and colder, and  
15 more affected by high wind speeds due to a stronger influence of katabatic winds from the  
16 inland ice, which can be assumed of being active also during the Holocene.

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21 The topographic position, the distance from the ice margin and the aspect seem to be mainly  
22 responsible for the type of vegetative cover, the soil distribution, and the thickness of the  
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25 155 active layer of the permafrost in the study area. Permafrost exists at depths < 20-30 cm at  
26 north facing slopes, where organic-rich permafrost is common. At south facing slopes  
27 permafrost has not been detected < 1 m. North facing (moist) slopes have dense vegetation  
28 and organic-rich soil horizons within the active layer, whereas south facing (dry) slopes or  
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## Materials and methods

### *Mapping and sedimentary analysis*

The geomorphological map (Figure 1b) is based on aerial photographs of the Danish Geodetic  
Institute (scale 1:40 000; Kort and Matrikelstyrelsen, 1968), publications from Scholz and  
Grottenthaler (1988) and Ten Brink (1975), and own field surveys in 2009 and 2011.

In total 187 samples for grain size analysis (Supplementary material Table S1) were taken in  
dunefields north, northwest and west to the glacial outwash plain (Figures 1b, 2b-d), and in  
four cross-sections through the valley with different distances from the recent ice margin.  
Each cross-section comprises 9 resp. 10 sampling points; section 1 (sampling points 10-19) is  
170 distal (ca. 4-5 km) and section 4 (sampling points 40-48) proximal (ca. 2-3 km) to the ice

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3 margin (Figure 1b). From each sampling point (10-48; Figure 1b) horizons at different depths  
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5 were described according to the guideline for soil description (FAO, 2006) and subsequently  
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7 sampled. At the cross-sections we refer to the upper 30 cm (maximum depth of active layer at  
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9 north facing slopes) as the upper layer and to the horizons below 30 cm as the lower layer of  
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11 the aeolian sand sheet, respectively.  
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14 Additional buried humic palaeosols (lower layer) - found under still active dunes (soil profiles  
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16 D0-D3, Figure 1b) - were sampled. For the upper layer (layer above the palaeosol as  
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18 described more detailed in Results) a soil texture hand test was done in field to determine  
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20 bands of different grain sizes. The grain size distribution of all samples was determined in the  
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22 laboratory after Blume et al. (2011) according to DIN ISO 11 277.  
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25 Furthermore, depth, width, length, inclination, and aspect of 16 selected deflation areas  
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27 (Supplementary material Table S2) were measured to get an overview where deflation is  
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29 active and which kind of material is subject to wind erosion.  
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32 Statistical analyses for grain size distribution patterns were implemented with the free  
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34 programming language R, version 3.1.2 (R Development Core Team 2014) by applying R-  
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36 packages *car* (Fox and Weisberg, 2011), and *RCMDR* (Fox, 2005).  
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#### 40 *Radiocarbon dating*

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42 Soil organic matter from the palaeosols was dated by AMS  $^{14}\text{C}$  dating in the laboratory of  
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44 Erlangen/Germany (abbr. Erl-; see Table 2). Calibration of  $^{14}\text{C}$  data was done with OxCal 4.2  
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46 (Bronk Ramsey, 2009). Radiocarbon dating was performed on 14 samples after pre-treatment  
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48 according to the acid-alkali-acid method: the samples were heated at 80°C in 1M HCl to  
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50 remove carbonates. Then, the samples were heated at 80°C in 1M NaOH to remove humic  
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52 acids and fulvic acids, respectively. Afterwards, the samples were heated at 80°C again in 1M  
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54 HCl to remove remaining carbonates. Finally, the samples were dried at 100°C, and stored in  
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56 closed glasses to avoid contamination. Six samples were taken from varying depths in profile  
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3 D1, and five samples from varying depths in profile D2 in the active dunefields (Figure 1b).  
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5 Additionally, the soil organic matter of three palaeosols of transects 1 to 3 were dated (profiles  
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7 17, 24, 33 in Figure 1b).  
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#### 11 *Optically stimulated luminescence dating*

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14 Four samples from profile D2 (sampling depths given in Table 3) were dated using both  
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16 quartz and feldspar optically stimulated luminescence (OSL). Sand grains ranging from 90-  
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18 180  $\mu\text{m}$  were obtained through wet-sieving the bulk sample (taken in opaque tubes), followed  
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21 205 by treatment with 10% HCl and 10% H<sub>2</sub>O<sub>2</sub> and subsequent density separation using fast float  
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23 (LST; potassium-rich feldspar  $\rho < 2.58 \text{ g cm}^{-3}$ , quartz  $\rho > 2.62 \text{ g cm}^{-3}$ ). The mineral extracts  
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25 were etched with 10% hydrofluoric acid (HF) for 30 minutes in case of feldspar, and with  
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27 40% HF for one hour in case of quartz, respectively. After etching, the samples were treated  
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29 with 30% HCl in order to remove any fluorides which might have built during the treatment.  
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32 210 Finally, the samples were washed with distilled water and dried at 50°C prior to re-sieving.

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34 The purity of the quartz extracts was tested following Duller (2003). All samples were  
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36 contaminated by feldspar, so the extracts were re-etched in 40% HF for 40 minutes, washed  
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38 and re-sieved. The subsequent purity test showed that the aggressive treatment would not  
39  
40 entirely remove the feldspar contribution to the OSL signal; thus this had to be done  
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43 215 instrumentally.

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45 The samples were measured using Risø TL/OSL readers (model DA-20; Thomsen et al. 2006)  
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47 equipped with a calibrated <sup>90</sup>Sr/<sup>90</sup>Y beta source and with both blue (470 nm) and infra-red  
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49 (IR; 870 nm) emitting diodes. The luminescence signals of the quartz extracts were detected  
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51 through a Hoya U-340 filter. Due to the feldspar contamination, the quartz was measured  
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54 220 using a double single-aliquot regenerative (dSAR) protocol (Banerjee et al., 2001). To find  
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56 suitable measurement settings, both a pre-heat plateau and thermal transfer were measured on  
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58 sample 143080 (cf. Table 3) with preheat temperatures ranging from 160°C to 300°C. The  
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cut-heat temperature following a test dose of  $\sim 5$  Gy was  $20^{\circ}\text{C}$  below the preheat temperature.

For each setting three aliquots were used, and the mean equivalent dose ( $D_e$ ) was calculated.

225 Based on the results (Supplementary material Figure S1), a pre-heat of  $200^{\circ}\text{C}$  (cut-heat  $180^{\circ}\text{C}$ ) was chosen. The pre-heat was followed by IR stimulation at  $50^{\circ}\text{C}$  (100 s) and a subsequent blue stimulation at  $125^{\circ}\text{C}$  (40 s). Each measurement cycle ended with a high temperature clean-out ( $280^{\circ}\text{C}$ ) using blue LEDs (40 s). For each sample,  $>30$  small aliquots (few tens of grains) were measured. The initial 0.2 s of the decay curve minus a background  
230 from the subsequent 1 s was used for calculation. The OSL signals are dominated by the fast component (Supplementary material Figure S2); however, less than 1% of the aliquots passed the rejection criteria (recycling ratio within 10%, test dose error within 20%, signal more than 3 sigma above background). It was therefore decided to not continue the quartz measurements but test the feldspar extracts instead.

235 For equivalent dose measurements of the potassium-rich feldspar extracts, a single aliquot regenerative (SAR) procedure was employed (Wallinga et al., 2000) on small aliquots (few tens of grains). IR stimulation was carried out at  $50^{\circ}\text{C}$  for 100 s after preheating at  $250^{\circ}\text{C}$  (60 s); the response to the test dose of 2.5 Gy was measured in the same manner, followed by an IR clean-out at  $280^{\circ}\text{C}$ . The luminescence signal was detected through a Schott BG39/Corning 7-  
240 59 filter combination. For each sample, twelve aliquots were measured, and the mean  $D_e$  was calculated. The signal collected during the initial 1.6 s of stimulation minus a background from the last 40 s was used for calculation. All aliquots passed the rejection criteria (recycling ratio within 10%, test dose error within 10%, signal more than 3 sigma above background). Dose recovery tests were conducted in order to test whether a given dose (prior to any  
245 heating) can be accurately recovered. Three aliquots per sample were bleached for 4 hours in a Hönle SOL2 and then given a dose of 16 Gy (test dose 2.5 Gy) prior to measurement. For all samples except 143080, given doses of were recovered within 10% of unity, whilst for sample 143080, the recovery was only within 20% of unity.

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3 As feldspar may suffer from anomalous fading (Wintle, 1973), which would result in an age  
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5 250 underestimate, the fading rate (g-value) was measured on six aliquots per sample following  
6  
7 Auclair et al. (2003). The same settings as for De determinations were used, and both several  
8  
9 prompt measurements and delays up to 10 hours were included. The fading correction is  
10  
11 based on Huntley and Lamothe (2001).  
12

13  
14 In order to determine the dose rate, the radionuclides (Table 3) were measured using high-  
15  
16 255 resolution gamma-spectrometry (Murray et al., 1987). The radionuclide concentrations were  
17  
18 converted into dose rates following Guérin et al. (2011), and the cosmic dose contribution was  
19  
20 added (Prescott and Hutton, 1994).  
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## 27 260 **Results**

### 28 *Aeolian deposits and landforms*

29  
30 Both small (< 50 cm height) and large (up to 2 m height) longitudinal dunes established  
31  
32 particularly in the transition zone from the glacial outwash plain to the dunefields (next to  
33  
34 profile D1, Figure 1b). The areas between these vegetated longitudinal dunes have no  
35  
36 vegetative cover. In addition, dome-shaped and barchan-like dunes are present in the  
37  
38 265 dunefields (Figure 2d); these become higher (>2 m) and larger with increasing distance from  
39  
40 the glacial outwash plain. Aeolian sand ripples (e.g. Anderson, 1987; Yizhaq et al., 2004) are  
41  
42 common both between and leeward of dunes, where steep sand ridges of several metres length  
43  
44 and width were found: These sand ridges are characterised by the absence of vegetation  
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49 270 (Figures 2c, d).  
50

51  
52 The depths of the aeolian sand sheet (Figure 1b) strongly depend on topographical features  
53  
54 and the distance from the ice margin. Greater depths of 50 cm or even > 100 cm (Table S1)  
55  
56 are found on wind-protected sites, e.g. in depressions and on leeward sides of moraines.  
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3 Deflation areas (Figure 1b) are widespread in the entire Umimmalissuaq valley and are  
4  
5 275 mainly present on S-SE facing slopes or on crests and S-SE facing parts of moraines (Table  
6  
7 S2). These often oval-shaped aeolian blow-outs are characterised by sparse or absent  
8  
9 vegetative cover, and cut deep into the aeolian sand sheet. Often the underlying moraine  
10  
11 material or bedrock is exposed by wind erosion. The size of deflation areas ranges from a few  
12  
13 to hundreds of metres in width and length, as well as their depth that ranges from around 1 m  
14  
15  
16 280 next to the present dunefields (e.g. deflation area 13; Table S2; Figure 1b) to around 30 cm  
17  
18 with increasing distance from the ice margin (e.g. 7, 9; Table S2; Figure 1b).  
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20

### 21 22 23 *Sedimentary units and grain size distribution*

24  
25 All soil profiles in the large dunefield (represented by D1-D3, Figure 1b) show alternating  
26  
27 285 sedimentary units of humus-free and humus-rich sediments. Buried humic palaeosols (Figure  
28  
29 3a: 1e-1g; Figure 3b: 2e-2h) can be taken as marker horizons dividing the profiles in an upper  
30  
31 and a lower layer. The palaeosols are developed in the lower layer consisting mainly of fine  
32  
33 sand and coarse silt (Figures 3a, b; for definition and contents of grain size fractions see Table  
34  
35 S1). According to FAO (2006), the main texture of palaeosols is silt loam, sometimes sandy  
36  
37 loam. The morphology of palaeosols visible in Figures 3c and 3d is characterised by a  
38  
39 290 continuous horizontal to subhorizontal alternating stratification of buried Ah and C horizons  
40  
41 with aeolian sand and silt. The centimeter to decimeter thick darker bands (Ah horizons)  
42  
43 indicate organic matter accumulation, which are separated by millimeter to centimeter thick  
44  
45 lighter bands (C horizons) of same soil texture (mostly silt loam). These bands feature a non-  
46  
47 horizontal structure perturbed by cryoturbational processes (cf. Figures 3a-d). Palaeosols are  
48  
49 295 covered by alternating bands (centimeter to decimeter) consisting of primarily coarse,  
50  
51 medium and fine sand (upper layer; Figures 3a-d). The main texture in the upper layer is  
52  
53 loamy coarse sand, but also sand is common, particularly in the uppermost bands. The clay  
54  
55 content of < 5 wt.% is negligible. In general, dune profiles show an abrupt decline in coarse  
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3 300 and medium sand and an increase in fine sand and silt content at the transition from upper to  
4 lower layer (Figures 3a, b), reaching up to 64 wt.% silt in profile D3.  
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10 Figure 3. (a) (b) (c) (d)  
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14 305 The main texture of the aeolian sand sheet (Figure 1b), represented by cross-sections 1 to 4, is  
15 silt loam: silt and sand contents range between 25 and 75 wt.% (Table S1). The lower layer of  
16 the aeolian sand sheet reaches partly close to 100 % sand (Figures 4a, d). Clay content with a  
17 mean of 4 wt.% is negligible.  
18  
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21  
22 The majority of sampling points from cross-sections 1 to 3 show finer grain sizes in the upper  
23 layer (mostly silt loam; Table 1, Figures 4b, d) and coarser grain sizes in the lower layer  
24 310 (mostly sandy loam, partly sand; Table 1, Figures 4a, d), whereas cross-section 4 is still more  
25 affected by coarser grain sizes in the upper layer (partly loamy coarse sand; Table 1, Figures  
26 4b, d). Within each cross-section the variability of grain sizes is very heterogeneous and is  
27 greater than between the respective cross-sections. Hereby, the variability of grain sizes in the  
28 upper layer of the cross-sections is distinctly lower and more homogeneous compared to the  
29 315 lower layer (Table 1, Figure 4d).  
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43 Table 1.  
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47 320 In general, sand contents significantly decrease with increasing distance from the ice margin  
48 (Pearson  $r = -0.29$ ,  $p < 0.001$ ), whereas silt contents increase ( $r = 0.27$ ,  $p < 0.001$ ). This is  
49 even more pronounced in the upper layers of dune profiles and sampling points (sand:  $r = -$   
50  $0.69$ ,  $p < 0.001$ ; silt:  $r = 0.68$ ,  $p < 0.001$ ; Figure 4e). However, the lower layers do not show a  
51 significant decline in grain sizes with increasing distance from the ice margin (sand:  $r = 0.09$ ,  
52  $p = 0.40$ ; silt:  $r = -0.13$ ,  $p = 0.25$ ; Figures 4a, d).  
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3 Grain sizes in the lower layer of dune sediments (palaeosols) are similar to grain sizes in the  
4 upper layer of cross-sections (texture: silt loam; Figures 4c, d; Table 1). A Levene test  
5 revealed variance homogeneity between palaeosols (lower layer) and the upper layers of  
6 cross-sections 1 to 4 ( $F = 0.23$ ,  $p = 0.92$ ). Using ANOVA ( $F = 1.51$ ,  $p = 0.20$ ) and following  
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12 330 Post-hoc Tukey test, we found no significant differences between grain sizes of palaeosols  
13 and cross-section 1 ( $p = 0.54$ ), cross-section 2 ( $p = 0.30$ ), cross-section 3 ( $p = 0.94$ ), and  
14 cross-section 4 ( $p = 0.99$ ). The grain sizes in upper layers of cross-sections 1 and 2, and cross-  
15 sections 3 and 4, respectively, are similar.  
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23 335 Figure 4. (a) (b) (c) (d) (e)  
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#### 26 27 *AMS $^{14}\text{C}$ ages*

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29 A summary of AMS  $^{14}\text{C}$  ages is given in Table 2. Soil organic matter from the palaeosol of  
30 profile D1 (Figure 3a) was dated to 330-57 cal yr b2k at a depth of 85 cm (Erl-19002), to  
31  
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34 340 1113-848 cal yr b2k at 95 cm (Erl-16621), and to 2731-2209 cal yr b2k at 140 cm (Erl-  
35 19003). The palaeosol of profile D2 (Figure 3b) yields ages of 110-92 cal yr b2k in 76 cm  
36 depth (Erl-16622), 2975-2795 cal yr b2k in 115 cm depth (Erl-16623), and 2749-2258 cal yr  
37 b2k in 140 cm depth (Erl-19004).  
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43 Samples taken from the cover sediments of the palaeosols and the transition zone between  
44  
45 345 cover sediments and palaeosols show very young and imprecise ages (Erl-16619, Erl-16620,  
46 Erl-16622, Erl-19002), caused by organic matter, which has been developed during the  
47 atomic age since 1945.  
48  
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51 Additionally, soil organic matter of buried palaeosols within cross-sections 1 to 4 was  
52 analysed. Sampling point 17 (Figures 1b, 5a) reveals an AMS  $^{14}\text{C}$  age of 5335-4919 cal yr  
53  
54  
55  
56 350 b2k (Erl-19000); this is so far the oldest age of soil organic matter from the valley bottom. A  
57 palaeosol from sampling point 33 (Figures 1b, 5c) has an AMS  $^{14}\text{C}$  age of 4876-4499 cal yr  
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3 b2k (Erl-16614). Soil organic matter from sampling point 24 (Figures 1b, 5b) was AMS  $^{14}\text{C}$   
4  
5 dated to 2975-2800 cal yr b2k (Erl-19001).  
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10 355 Table 2.  
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14 *Luminescence ages*  
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16 The total dose rates to feldspar taken from profile D2 vary between  $2.04 \pm 0.07$  Gy/ka  
17 (sample 143081; cf. Table 3) and  $2.37 \pm 0.08$  Gy/ka (sample 143078). The equivalent doses  
18  
19 (D<sub>e</sub> values) are more variable: The largest D<sub>e</sub> of  $12.8 \pm 0.8$  Gy was observed for sample  
20 360 (D<sub>e</sub> values) are more variable: The largest D<sub>e</sub> of  $12.8 \pm 0.8$  Gy was observed for sample  
21 143079 (D2-53), and the smallest ( $2.4 \pm 0.1$  Gy) for sample 143080). The IRSL ages given  
22 are all fading corrected; the g-values vary between  $2.87 \pm 0.03$  %/decade (143080) and  $3.81 \pm$   
23  $0.17$  %/decade (143078). In palaeosol D2, the uppermost sample (20 cm depth) was dated to  
24  $2.2 \pm 0.1$  ka, while the sample at a depth of 53 cm (143079) has an IRSL age of  $7.3 \pm 0.6$  ka.  
25  
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31 365 Sample 143080, just 16 cm below sample 143079, was dated to  $1.4 \pm 0.1$  ka, whilst the  
32 lowermost sample (143081) at a depth of 115 cm resulted in  $3.7 \pm 0.2$  ka.  
33  
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36 It is apparent that age inversions are present, i.e. the upper horizons show older ages than the  
37 lower ones. A possible cause for this might be age overestimation of the upper layers due to  
38 incomplete luminescence signal re-setting while the grains were being transported. The higher  
39 sand content of these two samples implies a shorter distance to the ice margin, which can  
40 result in poorer signal re-setting (e.g. Alexanderson and Murray, 2012). Further, it is possible  
41 that the material was mainly transported during winter months; in this case the sand will not  
42 have seen much daylight prior to its deposition. However, it is also possible that the ages of  
43 370 the lower samples are erroneous (dose recovery of sample 143080 was poor). A greater set of  
44 samples will be needed to investigate these issues in detail. Further, as the quartz OSL did not  
45 give any results to compare the IRSL ages with, we reject the OSL data for any further  
46 discussion but do point out that there is partial agreement with the AMS  $^{14}\text{C}$  data (see below).  
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5 Table 3.  
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9 Figure 5. (a) (b) (c)  
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### 13 **Discussion**

#### 14 *Linking aeolian processes and palaeosols*

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18 385 The main requirements for aeolian transport of sand and silt across the Umimmalissuaq valley  
19 are (i) sufficient supply of coarse-grained and fine-grained material from the glacial outwash  
20 plain and (ii) the frequently blowing katabatic winds combined with (iii) the peculiar arid  
21 climate conditions at the ice margin (cf. Bullard and Austin, 2011).  
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27 Coarse-grained material (predominantly medium sand and coarse sand, upper layer; Figures  
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29 390 3a, b, 4b; Table S1) is deposited predominantly in the active dunefields (Figure 1b) north,  
30 northwest and west of the glacial outwash plain. Scholz and Grottenthaler (1988) propose  
31 that, with the exception of active dunefields, no recent accumulation of aeolian material takes  
32 place in the study area. However, dust clouds have been observed to rise up to several  
33 hundreds of meters in the study area during summer. Even ice-near areas are covered by a  
34 thin layer of fine sand and silt after such events (cf. German, 1971; Willemse et al., 2003).  
35  
36 395 This may also currently provide durable (if combined with rainfall) sedimentation of fine sand  
37 and silt (upper layer of cross-sections in Figures 4b, d, e) in most parts of the Umimmalissuaq  
38 valley. Most likely, these events are stronger in winter because of a higher wind drift potential  
39 during this time of the year (e.g. Willemse, 2000), and the outwash-source zone is dry and  
40 unprotected against aeolian erosion (Schaetzel and Loope, 2008).  
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52 Deflation areas are widespread in the study area (Figure 1b), also in active dunefields. These  
53 deflation areas occur in the older aeolian sand sheet consisting of fine material, and hereby  
54 predominantly on wind exposed S-SE slopes and moraines with depths up to 1 m and areas  
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3 from a few up to hundreds of m<sup>2</sup> (Table 5). Similarly, Dijkmans and Törnqvist (1991)  
4  
5 405 describe a SE-NW orientation of these often bowl-shaped or oval-shaped aeolian blow-outs,  
6  
7 sometimes up to 1 m deep with diameters of up to several tens of meters (cf. French, 2007).  
8  
9 These frequently occurring blow-outs imply reworking of previously deposited sand and silt  
10  
11 by wind, and wind erosion as the prevailing aeolian process outside the dunefields.  
12  
13 Within the active dunefields 1-2 km from the ice margin (Figure 1b), humic palaeosols (lower  
14  
15 410 layer, consisting of silt loam, Figures 3a, b) are developed in older sand sheets and preserved  
16  
17 by deposition of the dune sands above (upper layer, consisting of loamy sand, Figures 3a, b).  
18  
19 Generally, (i) the proportion of finer grain sizes (clay, silt) in the dunefields with < 15 wt.% is  
20  
21 very small, (ii) the underlying cumulic palaeosols with finer material have no layers with  
22  
23 coarser material comparable to the overlying dunes. According to Ten Brink (1975) the  
24  
25 415 palaeosols are located within the Ørkendalen moraine system (Figure 1b). Hence, the lower  
26  
27 layer, in which the palaeosols have formed, must have accumulated after the formation of the  
28  
29 Ørkendalen moraines, since the lower layer is clearly not of glacial origin. At that time, the  
30  
31 ice had disappeared and a decreasing influence of the strong and dry katabatic winds affected  
32  
33 moisture conditions and thus the availability of sediments, soil formation and correspondingly  
34  
35 420 vegetation in the valley. Further, the dominance of pedogenesis after the formation of the  
36  
37 Ørkendalen moraines reflects a balance between pedogenesis and the sedimentation rate, i.e.  
38  
39 the cumulic palaeosols (with grain sizes predominantly of fine sand and coarse silt, Figures  
40  
41 3a-d) of more than 60 cm thickness represent a phase with lower intensity of aeolian activity  
42  
43 and synsedimentary pedogenesis. During that period of time, the sedimentation rate generally  
44  
45 425 and particularly of coarse-grained material (sand) decreased which favoured pedogenic  
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47 processes. However, thin lighter layers between thicker organic rich layers within the buried  
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49 Ah horizons suggest intermittent sedimentation events during soil formation. These  
50  
51 observations indicate that there was an episodically easily available source of fine to medium  
52  
53 sand in the source area, and quickly colonising sedges and other vascular plants in the  
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3 430 sedimentation area. Thus, pedogenesis became more intense during periods with decreasing  
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5 sedimentation rates and vice versa. It is important to notice that the soil formation after the  
6  
7 formation of the Ørkendalen moraines does not reflect an on-off system of aeolian  
8  
9 sedimentation. Instead, alternating periods of enhanced and weaker soil formation occurred  
10  
11 depending on the sedimentation rate. Cryoturbation features in the palaeosols of show the soil  
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14 435 horizons of palaeosols D1 and D2 (Figures 3a-d) were partly subject to cryoturbation and  
15  
16 alternating of frost-thaw processes during the period of soil formation. This has to be also  
17  
18 taken into account when interpreting any dating ages.  
19

20  
21 Since the ages from the lower boundaries of the palaeosols above the permafrost date back to  
22  
23 2731-2209 cal yr b2k (D1, 140 cm, Figure 3a) and 2749-2258 cal yr b2k (D2, 140 cm, Figure  
24  
25 440 3b), and the ages of the upper parts of the palaeosols date back to 330-57 cal yr b2k (D1, 85  
26  
27 cm, Figure 3a) and 110-92 cal yr b2k (D2, 76 cm, Figure 3b), a period of at least 2400 years  
28  
29 of relatively stable conditions related to pedogenesis is very likely. Interestingly, we found  
30  
31 with 2975-2795 cal yr b2k in 115 cm of profile D2 an older age than in 140 cm (Figure 3b).  
32  
33 This inversion of ages may reflect a rejuvenation effect, which is likely caused by an  
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35  
36 445 accumulation of younger humic substances above the permafrost table. A reason for that may  
37  
38 be also cryoturbation processes, which led to relocation of soil organic matter (Bockheim,  
39  
40 2007).  
41

42  
43 A sample from the oldest parts of a palaeosol in the Umimmalissuaq valley yielded a  
44  
45 relatively young TL (Thermoluminescence) age indicating the onset of soil formation after the  
46  
47 450 Ørkendalen period around 1380-980 ka (Scholz and Grottenthaler, 1988). Even though little  
48  
49 information is provided on the TL data, one has to assume an age underestimate as anomalous  
50  
51 fading has not been taken into account at that time. Ages from palaeosols in Sandflugtdalen  
52  
53 indicate a distinct earlier beginning of soil formation around 4680-4490 cal yr b2k (UtC-2034,  
54  
55 Van Tatenhove et al., 1996). Our data for the start of soil formation are similar to 3869-3123  
56  
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58 455 cal yr b2k (UtC-5624; Willemsse et al., 2003), to 3442-3263 cal yr b2k (GrN-14655; Dijkmans  
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3 and Törnqvist, 1991), and to 3.19-2.67 ka (UIC-1556) and 3.16-2.69 ka (UIC-1558; Forman  
4  
5 et al., 2007; all from Sandflugtdalen and Ørkendalen, respectively). Two buried organic layers  
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7 in Sandflugtdalen, which indicate the onset of soil formation, reveal younger ages of 1941-  
8  
9 1236 cal yr b2k and 1866-1232 cal yr b2k (Ozols, 2003). The results from the  
10  
11 460 Umimmalissuaq valley indicate an earlier start of soil formation than discussed above. This  
12  
13 may be confirmed in the future, since the base of the organic rich permafrost was not reached  
14  
15 in profiles D1 and D2 in 2011. The lowermost AMS <sup>14</sup>C ages are from top of the permafrost  
16  
17 table.  
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21 In the study area, aeolian activity intensified after around 300 cal yr b2k (Erl-16620, Erl-  
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23 465 19002, Table 2), and medium to coarse sand (Figures 3a, b) was transported from a nearby  
24  
25 available source forming dunefields (upper layer), which cover the palaeosols in the foreland  
26  
27 of the active ice margin. This suggests a markedly increasing sedimentation rate of coarse-  
28  
29 grained material. Most likely, these processes have been caused by a close ice margin  
30  
31 followed by stronger dry katabatic winds and changes in sediment supply when the formation  
32  
33 470 of the dunefields began. This would explain also the distinct coarser grain sizes compared to  
34  
35 the lower layer. The more or less continuous redistribution (erosion and accumulation) of  
36  
37 predominantly coarse-grained sand by intensive and prevailing aeolian activity in the area of  
38  
39 the dunefields limited further soil formation since then. Despite landscape heterogeneity in  
40  
41 the study area, only the outwash plain and the adjacent terminal moraines (ice-cored  
42  
43 475 moraines) can be the present sediment source (Figure 1b).  
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47 All these findings lead us to the assumption that the sedimentation of the coarse material in  
48  
49 the dunefields is connected to an advancing ice margin and its sandur area (if present),  
50  
51 representing the source of the coarse material. This means additionally that a period of time  
52  
53 with predominant deposition of fine material is most likely related to a more easterly situated  
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55 480 ice margin, because the lacking of coarse material in the lower layer of dunefields.  
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3 Compared to our results, a (re)accumulation of aeolian sand after the period of soil formation  
4 in Ørkendalen and Sandflugtdalen is assumed to have started earlier around 595-550 cal yr  
5 b2k (UtC-5619; Willemse et al., 2003), and 735-560 cal yr b2k (GrN-14651; Dijkmans and  
6  
7 Törnqvist, 1991; for further data see Table 2). The different timings of the sedimentation of  
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12 485 wind-blown coarser material could be interpreted related to the ice margin in the way, that the  
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14 Late Holocene advance of the ice reached the present ice margin in the Umimmalissuaq  
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16 valley later than in northerly adjacent valleys.  
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#### 20 21 *Implications for the deglaciation history of the Umimmalissuaq valley*

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23 490 The ice margin in West Greenland in general is assumed to have reached its present position  
24 already around 6000 yr BP, followed by a minimum extent behind the present ice margin at  
25 around 4000 yr BP during the Holocene thermal maximum (Ten Brink and Weidick, 1974;  
26  
27 Simpson et al., 2009). Since that time the ice sheet advanced again to its recent limits and  
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29 further, resulting in younger moraine deposits (e.g. Ørkendalen, Figure 1b). Several different  
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34 495 data exist for the Ørkendalen moraine system in West Greenland: it has been dated to 700-300  
35 BP (Ten Brink, 1975; UW-180, Table 2) and to 2.5-1.5 ka (Scholz and Grottenthaler, 1988).  
36  
37 In great contrast, other studies date the Ørkendalen moraine system to  $6.8 \pm 0.3$  ka by  $^{10}\text{Be}$   
38 (Levy et al., 2012) and to  $6.8 \pm 0.3$  cal ka b2k (UtC-1987, UtC-1990; Van Tatenhove et al.,  
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41  
42  
43 1996; Table 2).  
44

45 500 In contrast, our AMS  $^{14}\text{C}$  data from soil organic matter of the overlying palaeosols in the  
46 Umimmalissuaq valley yielded a minimum age of 2749-2258 cal yr b2k (Erl-19004, Table 2)  
47  
48 for the Ørkendalen moraines, most likely even older (cf. 2975-2795 cal yr b2k, Erl-16623).  
49  
50 Our data are in line with the proposed 3450 cal yr b2k (UtC-5624; Willemse et al., 2003) and  
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53  
54 3350 cal yr b2k (GrN-14655; Dijkmans and Törnqvist, 1991) for the recession of the ice  
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56 505 margin in Sandflugtdalen and Ørkendalen. After development of the Ørkendalen moraines the  
57 inland ice melted again at its margin and retreated beyond its present limit. Previous studies  
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3 proposed a former recession of the ice margin in West Greenland after formation of the  
4 Ørkendalen moraines of more than 10 kilometres (Weidick, 1985; Scholz and Grottenthaler,  
5 1988), or even of 16 kilometres (Van Tatenhove et al., 1996). The changing distance from the  
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10 510 ice margin to the outwash-source zone after formation of the Ørkendalen moraines affected  
11 the formation of soils, aeolian sand sheets and dunefields in the study area (cf. Willemse et  
12 al., 2003). Since grain sizes decrease significantly with increasing distance from the ice  
13 margin (Figure 4e), and since grain sizes and their variability within the upper layer of cross-  
14 section 1 (silt contents:  $54 \pm 6$  wt.%; Table 1, Figures 4c, d) 4-5 km west of the present ice  
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21 515 margin are comparable to palaeosols covered by coarse-grained dunes (silt contents:  $49 \pm 9$   
22 wt.%; Table 1, Figures 4c, d), we propose a transport distance of the fine aeolian sediments,  
23 in which the palaeosols have formed, of < 4 kilometres from inboard of the present ice  
24 margin.  
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29 AMS  $^{14}\text{C}$  ages of 5335-4919 cal yr b2k (sampling point 17), 4876-4499 cal yr b2k (33), and  
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31 520 2975-2800 cal yr b2k (24) (Figure 1b, Table 2) indicate soil formation also before 2749-2258  
32 cal yr b2k (Erl-19004; Table 2). These palaeosols are situated between 4 and 5 km away from  
33 the present ice margin. All sampling points are located within the Umîvît/Keglen moraines  
34 (according to Ten Brink, 1975). This further implies a recession of the ice margin between the  
35 Umîvît/Keglen stage (with 7300 cal yr b2k, UtC-1987, UtC-1990, after Van Tatenhove et al.,  
36 1996, Table 2) and the Ørkendalen stage at least around 2700 cal yr b2k (Erl-19004; Table 2).  
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43 As a consequence of lacking additional luminescence or  $^{10}\text{Be}$  ages from the glacial sediments  
44 in the Umimmalissuaq valley the precise boundary between Umîvît/Keglen and Ørkendalen  
45 moraines is not clear.  
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## 51 52 53 530 **Conclusions**

54  
55 During the Holocene the Umimmalissuaq valley has strongly been influenced by aeolian  
56 activities. This valley has a characteristic east-west orientation like numerous other valleys in  
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3 West Greenland, and herewith the observed phenomena can be generally taken as  
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5 representative for other valleys close to the ice margin in West Greenland.  
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7 535 Currently deflation – predominantly caused by easterly katabatic winds – redistributes aeolian  
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9 sand sheets (silt loam) further west and forms active dunefields (consisting of loamy coarse  
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11 sand and sand). Active dunefields occur particularly at south facing slopes north, northwest  
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13 and west to the glacial outwash plain within around 2 km of the present ice margin. The data  
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15 of grain size distribution, and AMS  $^{14}\text{C}$  data of the soils in the Umimmalissuaq valley lead to  
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18 540 the following findings:

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21 1. Aeolian activity intensified after around 300 cal yr b2k and the still active dunefields  
22  
23 with coarse and medium sand accumulation (upper layer) developed. Thus we infer  
24  
25 the ice margin must have reached its present position around 300 cal yr b2k.  
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28 2. Palaeosols with humic A horizons located within the Ørkendalen moraine system are  
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30 545 developed in fine-grained aeolian sediment (silt loam - lower layer). They are covered  
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32 by coarse-grained aeolian bands (loamy coarse sand to sand - upper layer). The lower  
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34 layer, in which the palaeosols have formed, shows grain sizes comparable to aeolian  
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36 sand sheets (upper layer), which are currently formed distal (in around 4 km distance)  
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38 to the ice margin. Thus, we assume a transport distance of the fine aeolian sediments  
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41 550 of the lower layer – buried under the present dunefield next to the ice margin – of at  
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43 least 4 kilometres from inboard of the present ice margin.

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45 3. AMS  $^{14}\text{C}$  dating of soil organic matter of these buried palaeosols yielded a minimum  
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47 age of 2749-2258 cal yr b2k for the start of soil formation. Since traces of moraine  
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49 material overlying the palaeosols could not be detected, this particular area must have  
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52 555 been ice-free since that time. A potential earlier start of soil formation may be  
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54 confirmed in the future, since the base of the organic rich permafrost was not achieved  
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56 in profiles D1 and D2 in 2011. In contrast, the lowermost AMS  $^{14}\text{C}$  ages from  
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58 palaeosols buried under the dunefield are from top of the permafrost table.  
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3 4. According to the youngest AMS  $^{14}\text{C}$  ages of the buried palaeosols a stable period of at  
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5 560 least 2400 years can be inferred during the Late Holocene, in which the area was  
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7 characterised by pedogenesis and low intensity of aeolian activity, but with constant  
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9 input of fine sand and silt (lower layer).  
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### 11 12 13 14 **Acknowledgements**

15  
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27 570

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## Tables

**Table 1.** Variability of grain sizes (data shown in wt.%) in dune sediments and the respective cross-sections; SD = standard deviation.

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**Table 2.** AMS  $^{14}\text{C}$  data and luminescence data of samples related to glacial, glaciofluvial and aeolian deposits in the Kangerlussuaq area, West Greenland, classified in the chronological context.

710 **Table 3.** Luminescence dating information, including radionuclide concentrations, water contents, dose rates (Dr), equivalent doses (De), g-values (i.e. fading rates) and (fading corrected) ages. Preference is given to the fading corrected ages. See text for details. n = number of aliquots measured to obtain average De's; s.e. = standard error.

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3 715 Figures  
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7 **Figure 1.** (a) Map of the area around Kangerlussuaq, West Greenland showing the study area  
8 and the adjacent valleys Sandflugtdalen and Ørkendalen; modified after Storms et al., 2012.  
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10 (b) Geomorphological map of the Umimmalissuaq valley based upon air-photo interpretation,  
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14 720 field evidence, and additional information in Ten Brink (1975).  
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18 **Figure 2.** (a) Recent moraine of Ørkendalen glacier overrunning current vegetation. Photo  
19 (2014) was taken towards northwest. (b) Umimmalissuaq valley with the glacial outwash  
20 plain and the large dunefield west/northwest of the outwash plain (for locations see Figure 1b)  
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25 725 - taken towards west/northwest. (c), (d) Large dunefield, glacial outwash plain and  
26 Ørkendalen glacier - (c) taken from profile D3 towards east, (d) taken from profile D2  
27 towards east.  
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34 **Figure 3.** Dune profiles D1 and D2 (for location see Figure 1b) showing buried humic  
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36 730 palaeosols and overlying dune sands. (a), (b) Profile sketches of D1 and D2 with AMS  $^{14}\text{C}$   
37 data of soil organic matter, IRSL data, grain size distribution and pedology. For unmarked  
38 bands a soil texture hand test was done in field. The darker the palaeosol the higher the  
39 amount of soil organic matter. In both profiles permafrost was detected below 140 cm. (c), (d)  
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47 735 Photos of profiles D1 and D2 showing palaeosols (lower layer) and overlying dune sands  
48 (upper layer). Traces of cryoturbation are present in both palaeosols.  
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52 **Figure 4.** (a), (b), (c) Soil texture ternary diagrams (data shown in wt.%). (a) Lower layer of  
53 cross-sections 1 to 4 compared to lower layer of dunefields. Dune profiles show relatively  
54 fine, the sampling points from cross-section 1 to 4 partly coarse grain sizes. (b) Upper layer of  
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59 740 cross-sections 1 to 4 compared to the upper layer of dunefields. Highest sand contents,  
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3 particularly in both coarse and medium sand range, were found in the dunefields. Cross-  
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5 section 4 has higher contents of sandy loam compared to cross-sections 1 to 3. (c) Lower  
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7 layer of dunefields compared to the upper layer of cross-section 1. Note that grain sizes from  
8  
9 the lower layer of dune profiles are in the same range as from the upper layer of cross-section  
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11 745 1. (d) Variability of sand content (wt.%) in the upper layer (UL) and lower layer (LL) of dune  
12  
13 sediments (Dunes) and cross-sections 1 to 4 (C1, C2, C3, C4). (e) Mean sand content (wt.%)  
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15 in the upper layer of dune sediments (filled dots) and cross-sections 1 to 4 (blank dots) with  
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17 increasing distance (m) from the ice margin.  
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23 750 **Figure 5.** Selected soil profiles from cross-sections showing grain size distribution, pedology  
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25 and AMS  $^{14}\text{C}$  data of soil organic matter. (a) Profile 17 (cross-section 1). (b) Profile 24 (cross-  
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27 section 2). (c) Profile 33 (cross-section 3). For location of soil profiles see Figure 1b.  
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7 **Table S1.** Grain size analysis of all soil samples. Abbreviations and grain size fractions: cS =  
8 coarse sand (0.63-2 mm), mS = medium sand (0.2-0.63 mm), fS/ffS = fine sand/very fine  
9 sand (fS: 0.125-0.2 mm, ffS: 0.063-0.125 mm), cU = coarse silt (0.02-0.063 mm), mU =  
10 medium silt (0.0063-0.02 mm), fU = fine silt (0.002-0.0063 mm), clay (< 0.002 mm). For  
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16 760 location of soil profiles see Figure 1b.  
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32 **Table S2.** Investigated deflation areas illustrating measured aspects, inclinations, widths,  
33 lengths and depths. Description of aspect: S=South, SE=Southeast. The aspect and inclination  
34 are related to the hosting slope and moraine. The locations of the investigated deflation areas  
35 are shown in Figure 1b with *italic numbers*.  
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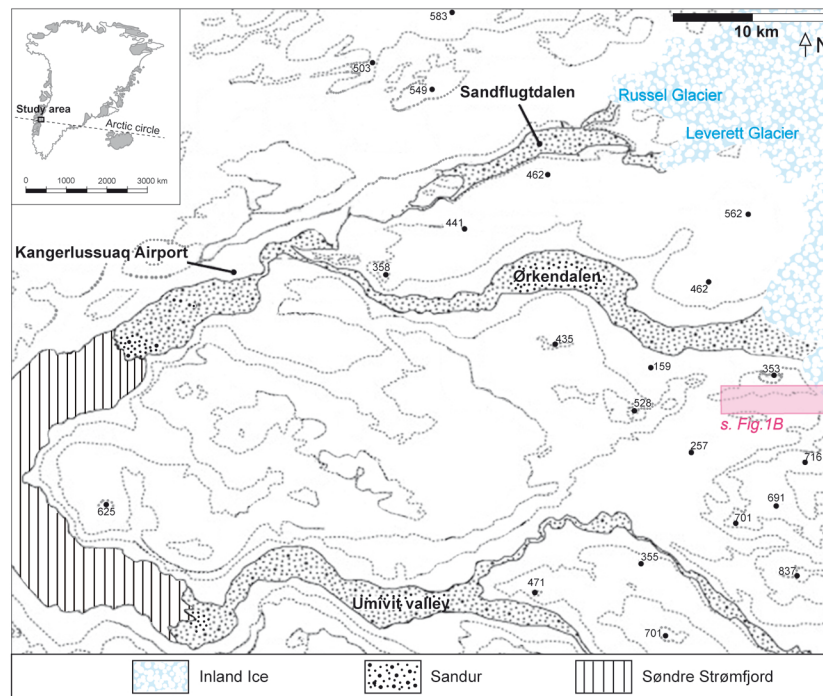
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31 **Figure S1.** OSL preheat plateau and thermal transfer for sample 143080. A preheat  
32 temperature of 200°C was chosen for the measurements.  
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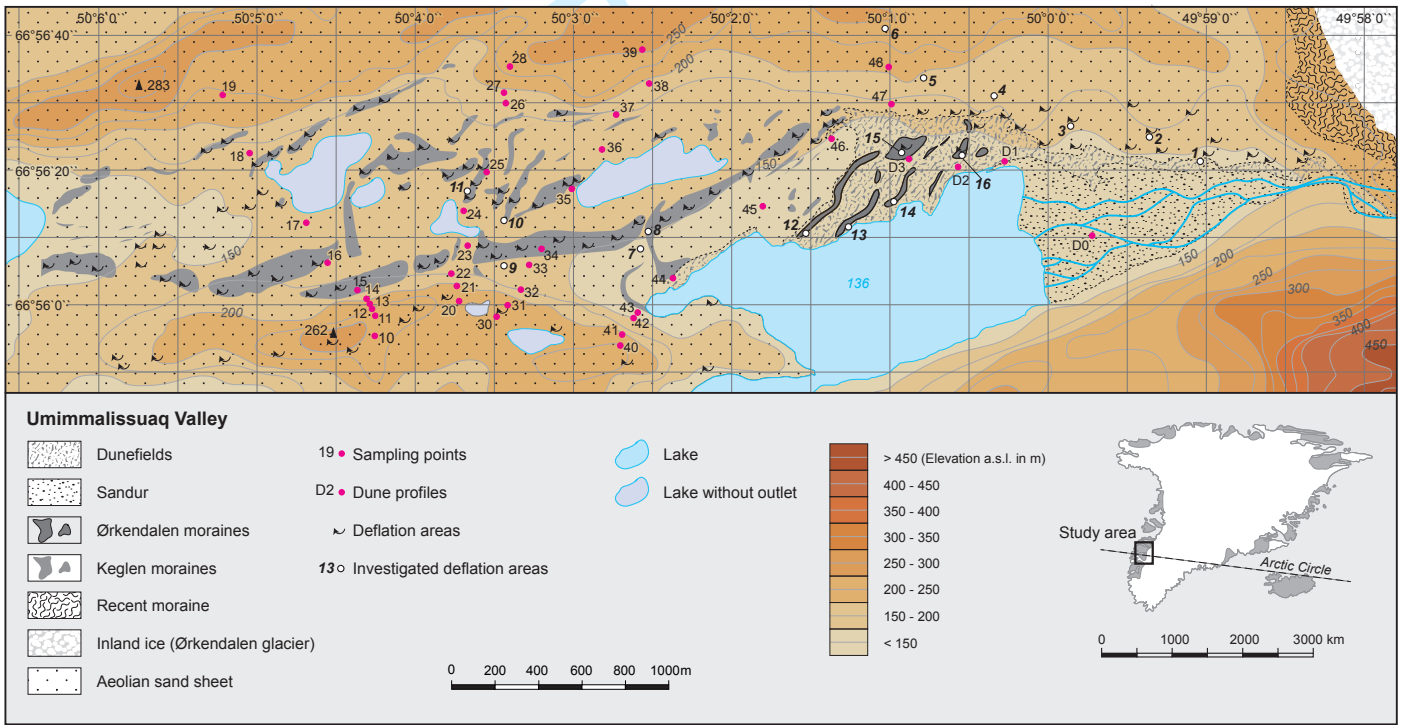
40 **Figure S2.** a) Natural and b) regenerated (7 Gy) quartz OSL decay curve of one aliquot of  
41 sample 143079. The fast decay implies the presence of the fast component.  
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32 Figure 2. (a) Recent moraine of Ørkendalen glacier overrunning current vegetation. Photo (2014) was taken  
33 towards northwest.

34 812x609mm (72 x 72 DPI)

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Figure 2. (b) Umimmalissuaq valley with the glacial outwash plain and the large dunefield west/northwest of the outwash plain (for locations see Figure 1b) - taken towards west/northwest.  
1219x812mm (72 x 72 DPI)

Review

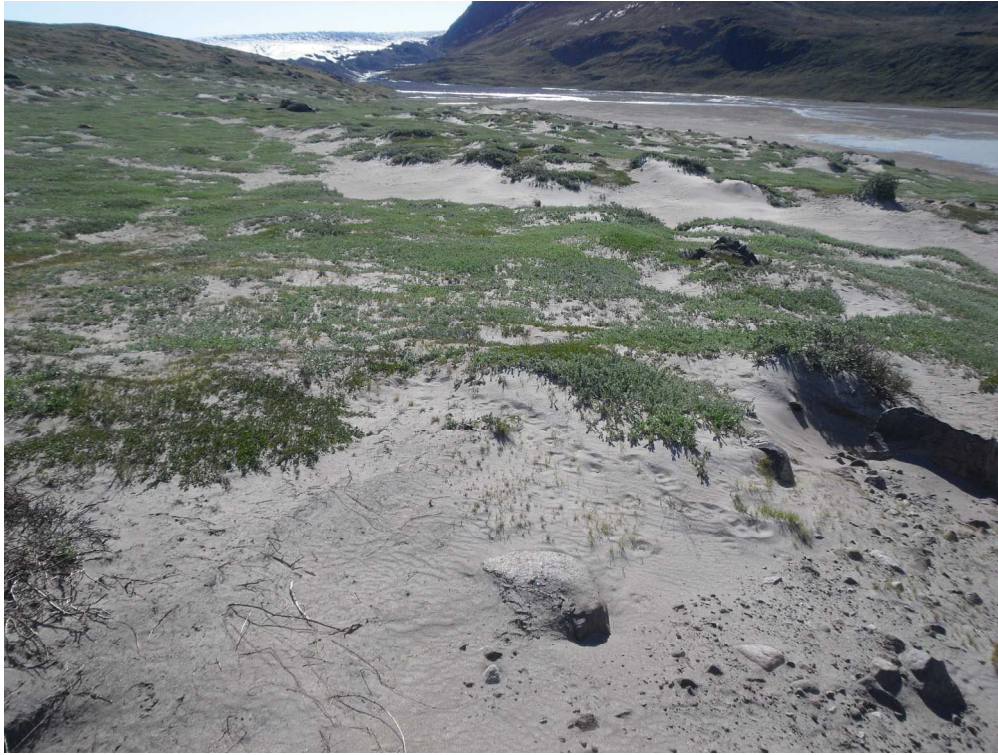


Figure 2. (c) Large dunefield, glacial outwash plain and Ørkendalen glacier - taken from profile D3 towards east.

812x609mm (72 x 72 DPI)

review

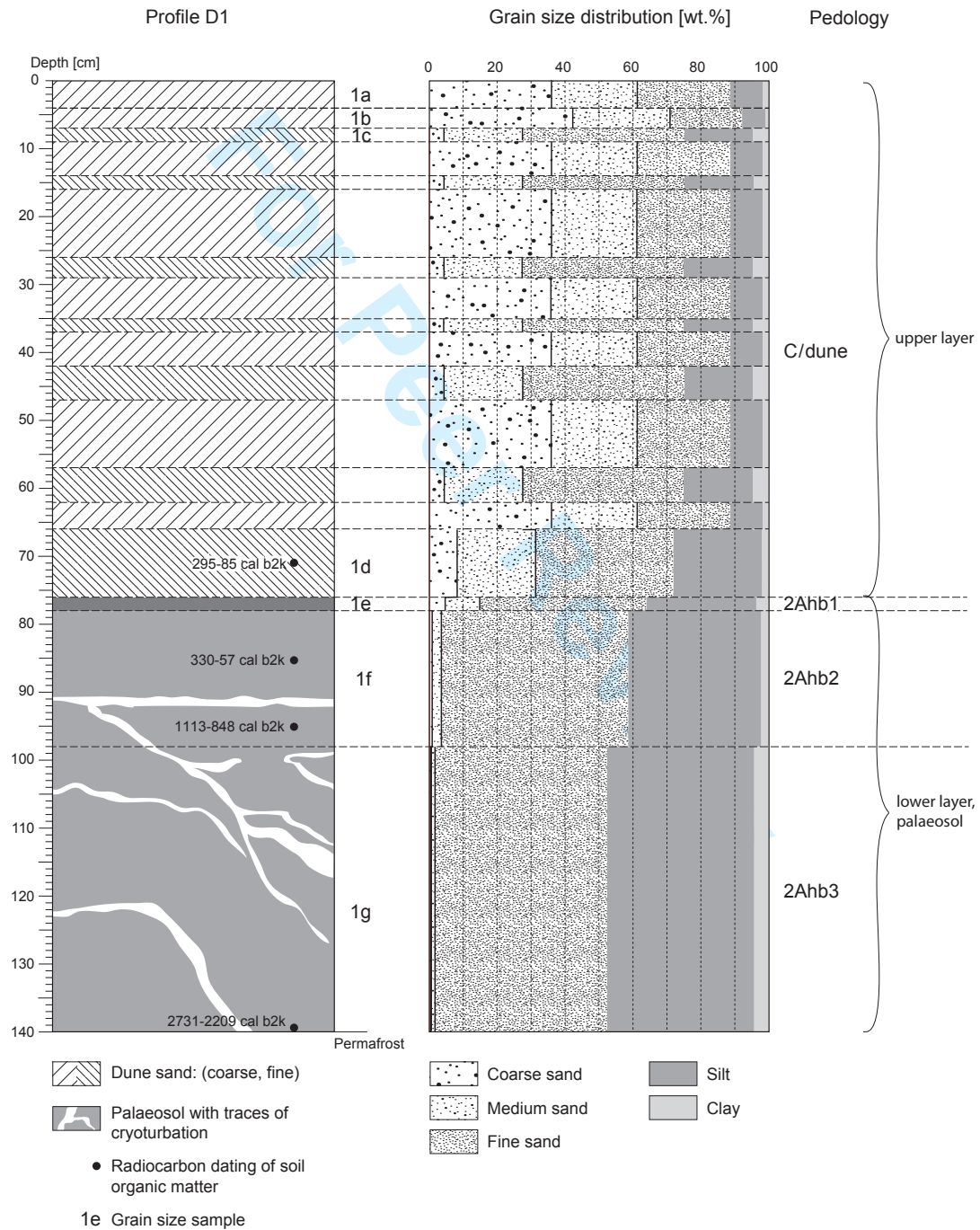
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Figure 2. (d) Large dunefield, glacial outwash plain and Ørkendalen glacier - taken from profile D2 towards east.  
1219x812mm (72 x 72 DPI)

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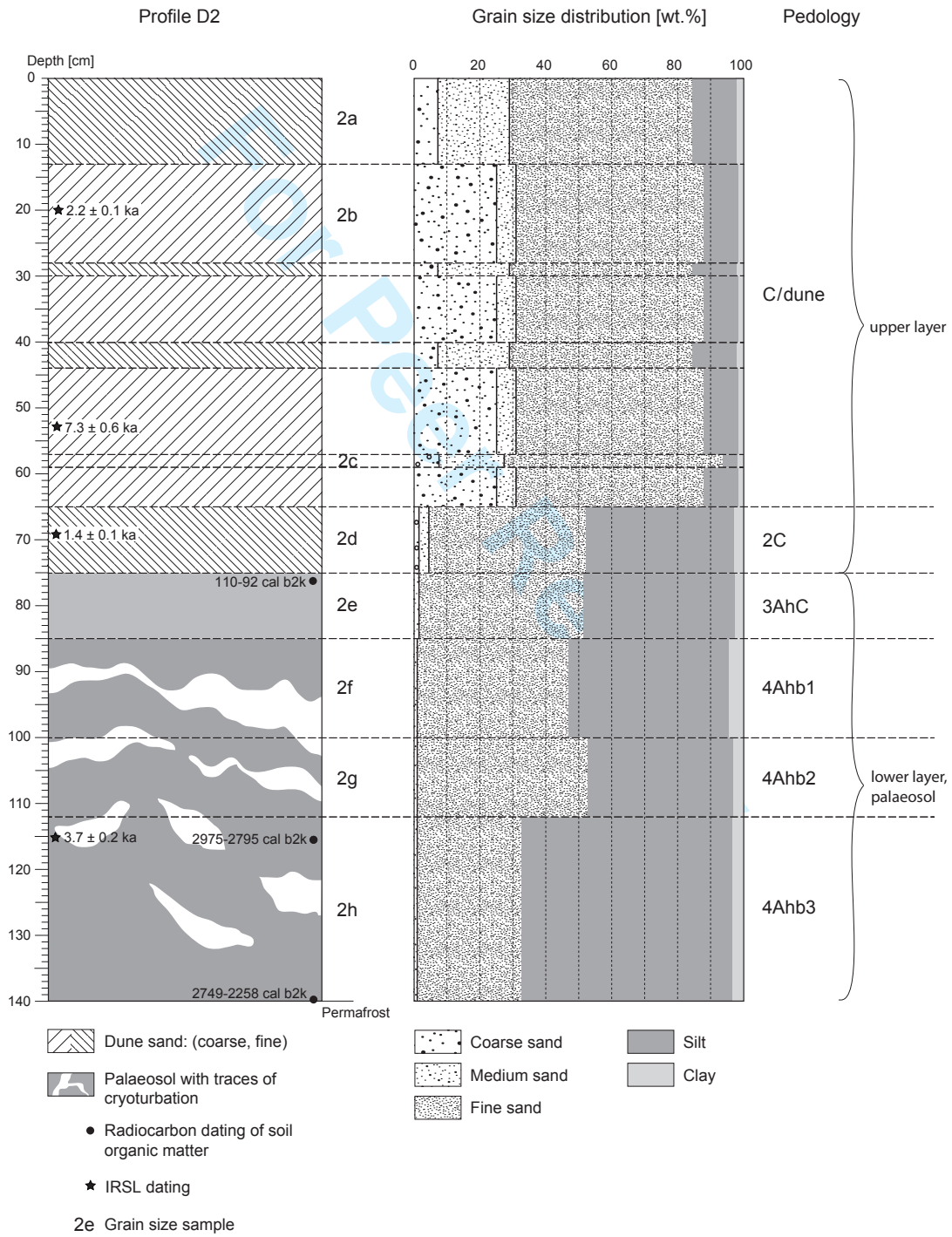




Figure 3. (c) Photo of profile D1 showing palaeosol (lower layer) and overlying dune sand (upper layer).  
Traces of cryoturbation are present in palaeosol.  
647x914mm (96 x 96 DPI)

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Figure 3. (d) Photo of profile D2 showing palaeosol (lower layer) and overlying dune sand (upper layer).  
Traces of cryoturbation are present in palaeosol.  
609x812mm (72 x 72 DPI)

| Sedimentary unit    | Location        | Sand ( $\pm$ SD) | Silt ( $\pm$ SD) | Clay ( $\pm$ SD) |
|---------------------|-----------------|------------------|------------------|------------------|
| Upper + lower layer | Dunes           | 63 $\pm$ 20      | 35 $\pm$ 19      | 2 $\pm$ 1        |
|                     | Cross-section 4 | 48 $\pm$ 16      | 49 $\pm$ 15      | 3 $\pm$ 2        |
|                     | Cross-section 3 | 49 $\pm$ 17      | 47 $\pm$ 16      | 4 $\pm$ 3        |
|                     | Cross-section 2 | 47 $\pm$ 16      | 50 $\pm$ 16      | 3 $\pm$ 2        |
|                     | Cross-section 1 | 46 $\pm$ 14      | 50 $\pm$ 14      | 4 $\pm$ 2        |
| Upper layer         | Dunes           | 85 $\pm$ 8       | 13 $\pm$ 7       | 2 $\pm$ 1        |
|                     | Cross-section 4 | 47 $\pm$ 12      | 49 $\pm$ 11      | 4 $\pm$ 2        |
|                     | Cross-section 3 | 44 $\pm$ 7       | 51 $\pm$ 7       | 5 $\pm$ 5        |
|                     | Cross-section 2 | 40 $\pm$ 7       | 57 $\pm$ 7       | 3 $\pm$ 2        |
|                     | Cross-section 1 | 42 $\pm$ 6       | 54 $\pm$ 6       | 4 $\pm$ 2        |
| Lower layer         | Dunes           | 48 $\pm$ 9       | 49 $\pm$ 9       | 3 $\pm$ 1        |
|                     | Cross-section 4 | 48 $\pm$ 21      | 50 $\pm$ 21      | 2 $\pm$ 2        |
|                     | Cross-section 3 | 55 $\pm$ 23      | 42 $\pm$ 22      | 3 $\pm$ 2        |
|                     | Cross-section 2 | 58 $\pm$ 21      | 39 $\pm$ 19      | 3 $\pm$ 3        |
|                     | Cross-section 1 | 50 $\pm$ 20      | 46 $\pm$ 18      | 4 $\pm$ 2        |

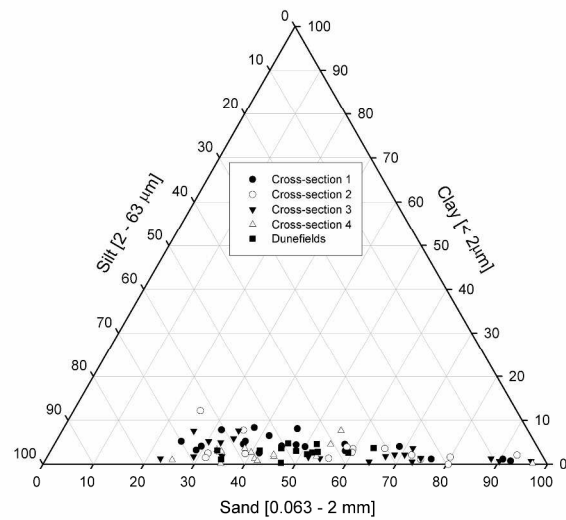


Figure 4. (a) Soil texture ternary diagrams (data shown in wt.%). Lower layer of cross-sections 1 to 4 compared to lower layer of dunefields. Dune profiles show relatively fine, the sampling points from cross-section 1 to 4 partly coarse grain sizes.  
296x420mm (300 x 300 DPI)

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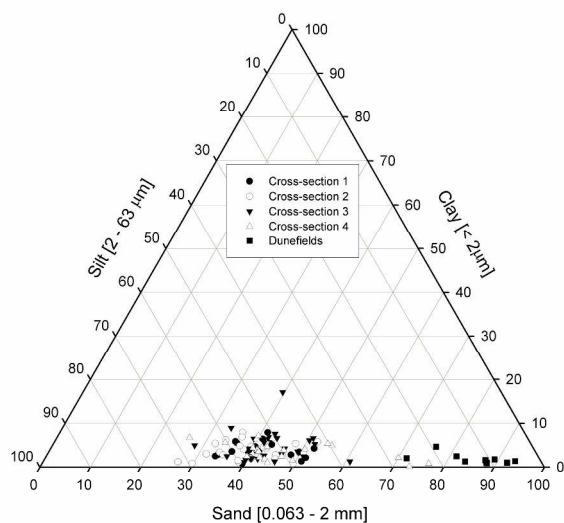


Figure 4. (b) Soil texture ternary diagrams (data shown in wt.%). Upper layer of cross-sections 1 to 4 compared to the upper layer of dunefields. Highest sand contents, particularly in both coarse and medium sand range, were found in the dunefields. Cross-section 4 has higher contents of sandy loam compared to cross-sections 1 to 3.

296x420mm (300 x 300 DPI)

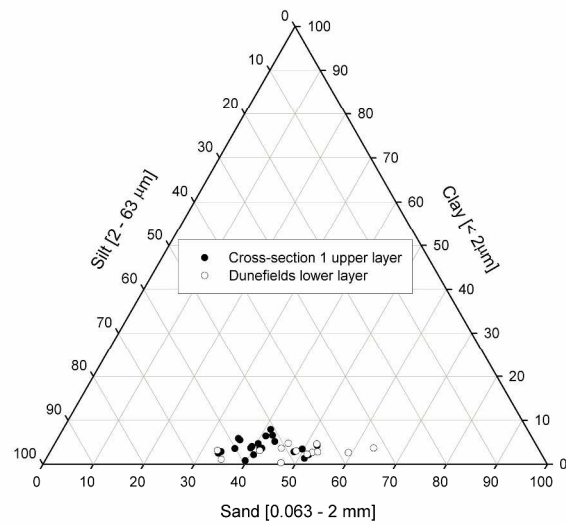


Figure 4. (c) Soil texture ternary diagrams (data shown in wt.%). Lower layer of dunefields compared to the upper layer of cross-section 1. Note that grain sizes from the lower layer of dune profiles are in the same range as from the upper layer of cross-section 1.  
296x420mm (300 x 300 DPI)

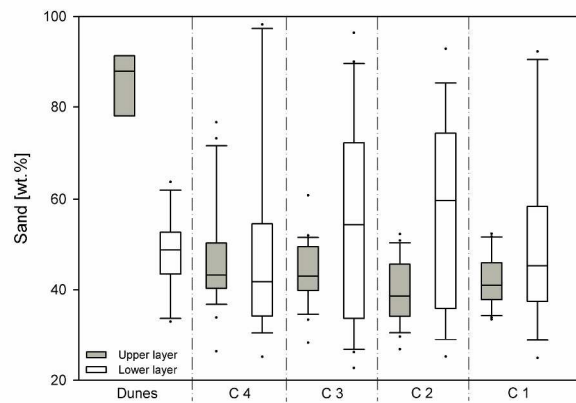


Figure 4. (d) Variability of sand content (wt.%) in the upper layer and lower layer of dune sediments (Dunes) and cross-sections 1 to 4 (C1, C2, C3, C4).  
296x420mm (300 x 300 DPI)



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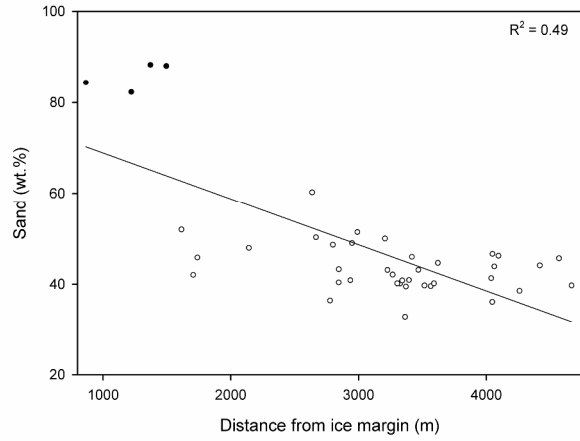


Figure 4. (e) Mean sand content (wt.%) in the upper layer of dune sediments (filled dots) and cross-sections 1 to 4 (blank dots) with increasing distance (m) from the ice margin.  
296x420mm (300 x 300 DPI)

| Chronological process  | Lab-No.                        | Sampling point/Location                           | Calibrated age [cal b2k] <sup>a</sup> | <sup>14</sup> C age [BP] | Luminescence age [ka] | <sup>10</sup> Be age [ka] | Material      | Depth [cm]               | Relevance [min./max. age]       | Reference                   |
|--|--------------------------------|---|---------------------------------------|--------------------------|-----------------------|---------------------------|---------------|--------------------------|---------------------------------|-----------------------------|
| Ørkendalen moraine formation                                   | UtC-1987                       | Sandflugtdalen (67.09°N/50.29°W)                  | 7533-7074                             | 6380±100                 |                       |                           | Gyttja (mud)  | 200                      | Max. Ørkendalen moraines        | Van Tatenhove et al. (1996) |
|  | UtC-1990                       | Sandflugtdalen (67.09°N/50.34°W)                  | 7208-6850                             | 6090±50                  |                       |                           | Gyttja (mud)  | No info                  | Max. Ørkendalen moraines        | Van Tatenhove et al. (1996) |
|  | LL0901-LL0911                  | Sandflugtdalen (67.11°N/50.29°W; 67.16°N/50.12°W) |                                       |                          |                       | 6.8±0.3                   | Boulders      | No info                  | Max. Ørkendalen moraines        | Levy et al. (2012)          |
|  | UIC-1558                       | Sandflugtdalen (no data)                          |                                       |                          | 3.2-2.7               |                           | Org. material | 35                       | Min. Ørkendalen moraines        | Forman et al. (2007)        |
|  | UIC-1556                       | Sandflugtdalen (no data)                          |                                       |                          | 3.0-2.9               |                           | Org. material | 28                       | Min. Ørkendalen moraines        | Forman et al. (2007)        |
|  | Erl-16623                      | D2/Umimmalissuaq valley (66.56°N/50.0°W)          | 2975-2795                             | 2709±50                  |                       |                           | Org. material | 112-117                  | Min. Ørkendalen moraines        | This study                  |
|  | Erl-19004                      | D2/Umimmalissuaq valley (66.56°N/50.0°W)          | 2749-2258                             | 2361±50                  |                       |                           | Org. material | 140                      | Min. Ørkendalen moraines        | This study                  |
|  | Erl-19003                      | D1/Umimmalissuaq valley (66.56°N/50.0°W)          | 2731-2209                             | 2333±51                  |                       |                           | Org. material | 140                      | Min. Ørkendalen moraines        | This study                  |
|  | No info                        | H1/Sandflugtdalen (no data)                       | 1941-1236                             | 1605±160                 |                       |                           | Org. material | 23-25                    | Min. Ørkendalen moraines        | Ozols (2003)                |
|  | No info                        | G1/Sandflugtdalen (no data)                       | 1866-1232                             | 1550±145                 |                       |                           | Org. material | 23-25                    | Min. Ørkendalen moraines        | Ozols (2003)                |
| No info  | Umimmalissuaq valley (no data) |   |                                       | 1.4-1.0                  |                       | Peaty silt                | 40            | Min. Ørkendalen moraines | Scholz and Grottenthaler (1988) |                             |
| UW-180   | Lake Ørkendalen (no data)      | 570-(-52)   | 330±75                                |                          |                       | Plant residues            | No info       | Min. Ørkendalen moraines | Ten Brink (1975)                |                             |
| Retreat of ice margin and start of soil formation (palaeosols) | UtC-2034                       | Sandflugtdalen (67.10°N/50.24°W)                  | 4680-4490                             | 4060±60                  |                       |                           | Peat          | No info                  | Start of soil formation         | Van Tatenhove et al. (1996) |

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| 5  |   | PS4-Russell/P1 Base                                      |           |          |                |         |   |                                  |
| 6  | UtC-5624  | Sandflugtdalen<br>(67.05°N/50.14°W)                      | 3869-3123 | 3200±130 | Plant residues | No info | Halt in aeolian sand<br>formation                                 | Willemse et al. (2003)           |
| 7  |   |  |           |          |                |         |   |                                  |
| 8  |   | Sand sheet Sandflugtdalen                                |           |          |                |         |   |                                  |
| 9  | GrN-14655   | (67.03°N, 50.24°W)                                       | 3442-3263 | 3095±40  | Sandy peat     | No info | Halt in aeolian sand<br>formation                                 | Dijkmans and Törnqvist<br>(1991) |
| 10 |   |  |           |          |                |         |   |                                  |
| 11 | Erl-16623   | D2/Ummimalissuaq valley<br>(66.56°N/50.0°W)              | 2975-2795 | 2709±50  | Org. material  | 112-117 | Min. Ørkendalen moraines,<br>start of soil formation              | This study                       |
| 12 |   |  |           |          |                |         |   |                                  |
| 13 | Erl-19004   | D2/Ummimalissuaq valley<br>(66.56°N/50.0°W)              | 2749-2258 | 2361±50  | Org. material  | 140     | Min. Ørkendalen moraines  | This study                       |
| 14 |   |  |           |          |                |         |   |                                  |
| 15 | Erl-19003   | D1/Ummimalissuaq valley<br>(66.56°N/50.0°W)              | 2731-2209 | 2333±51  | Org. material  | 140     | Min. Ørkendalen moraines  | This study                       |
| 16 |   |  |           |          |                |         |   |                                  |
| 17 |   |  |           |          |                |         |   |                                  |
| 18 |   |  |           |          |                |         |   |                                  |
| 19 | Readvance of ice<br>margin and<br>(re)accumulation of<br>aeolian sand |  |           |          |                |         |   |                                  |
| 20 | Erl-16621   | D1/Ummimalissuaq valley<br>(66.56°N/50.0°W)              | 1113-848  | 1041±50  | Org. material  | 93-98   | Halt in soil formation and<br>(re)accumulation of aeolian<br>sand | This study                       |
| 21 |   |  |           |          |                |         |   |                                  |
| 22 |   |  |           |          |                |         |   |                                  |
| 23 | Erl-19002   | D1/Ummimalissuaq valley<br>(66.56°N/50.0°W)              | 330-57    | 123±47   | Org. material  | 85      | Halt in soil formation and<br>(re)accumulation of aeolian<br>sand | This study                       |
| 24 |   |  |           |          |                |         |   |                                  |
| 25 | Erl-16620   | D1/Ummimalissuaq valley<br>(66.56°N/50.0°W)              | 295-85    | -204±45  | Org. material  | 66-76   | Halt in soil formation and<br>(re)accumulation of aeolian<br>sand | This study                       |
| 26 |   |  |           |          |                |         |   |                                  |
| 27 | Erl-16622   | D2/Ummimalissuaq valley<br>(66.56°N/50.0°W)              | 110-92    | -349±44  | Org. material  | 71-76   | Halt in soil formation and<br>(re)accumulation of aeolian<br>sand | This study                       |
| 28 |   |  |           |          |                |         |   |                                  |
| 29 |   |  |           |          |                |         |   |                                  |
| 30 |   |  |           |          |                |         |   |                                  |
| 31 | GrN-14651   | Sand sheet Ørkendalen<br>(67.0°N/50.28°W)                | 735-560   | 610±80   | Peaty silt     | No info | (Re)accumulation of<br>aeolian sand                               | Dijkmans and Törnqvist<br>(1991) |
| 32 |   |  |           |          |                |         |   |                                  |
| 33 | UtC-5619  | PS4-Russell/P1 Top<br>Sandlugtdalen<br>(67.05°N/50.14°W) | 595-550   | 487±30   | Plant residues | No info | (Re)accumulation of<br>aeolian sand                               | Willemse et al. (2003)           |
| 34 |   |  |           |          |                |         |   |                                  |
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|-----------------|-----------|---|-----------|---------|---------------|-------|---|------------|
| Additional data | Erl-19000 | 17/ Umimmalissuaq valley<br>(66.56°N/50.47°W) | 5335-4919 | 4433±54 | Org. material | 50    | Min. Umivít/Keglen, max.<br>Ørkendalen moraines | This study |
|                 | Erl-16614 | 33/Umimmalissuaq valley<br>(66.56°N/50.33°W)  | 4876-4499 | 4114±53 | Org. material | 60-62 | Min. Umivít/Keglen, max.<br>Ørkendalen moraines | This study |
|                 | Erl-19001 | 24/ Umimmalissuaq valley<br>(66.56°N/50.37°W) | 2975-2800 | 2720±49 | Org. material | 80    | Min. Umivít/Keglen, max.<br>Ørkendalen moraines | This study |
|                 | Erl-16619 | D0/Umimmalissuaq valley<br>(66.56°N/49.59°W)  | 310-76    | 7±45    | Org. material | 44-47 |   | This study |

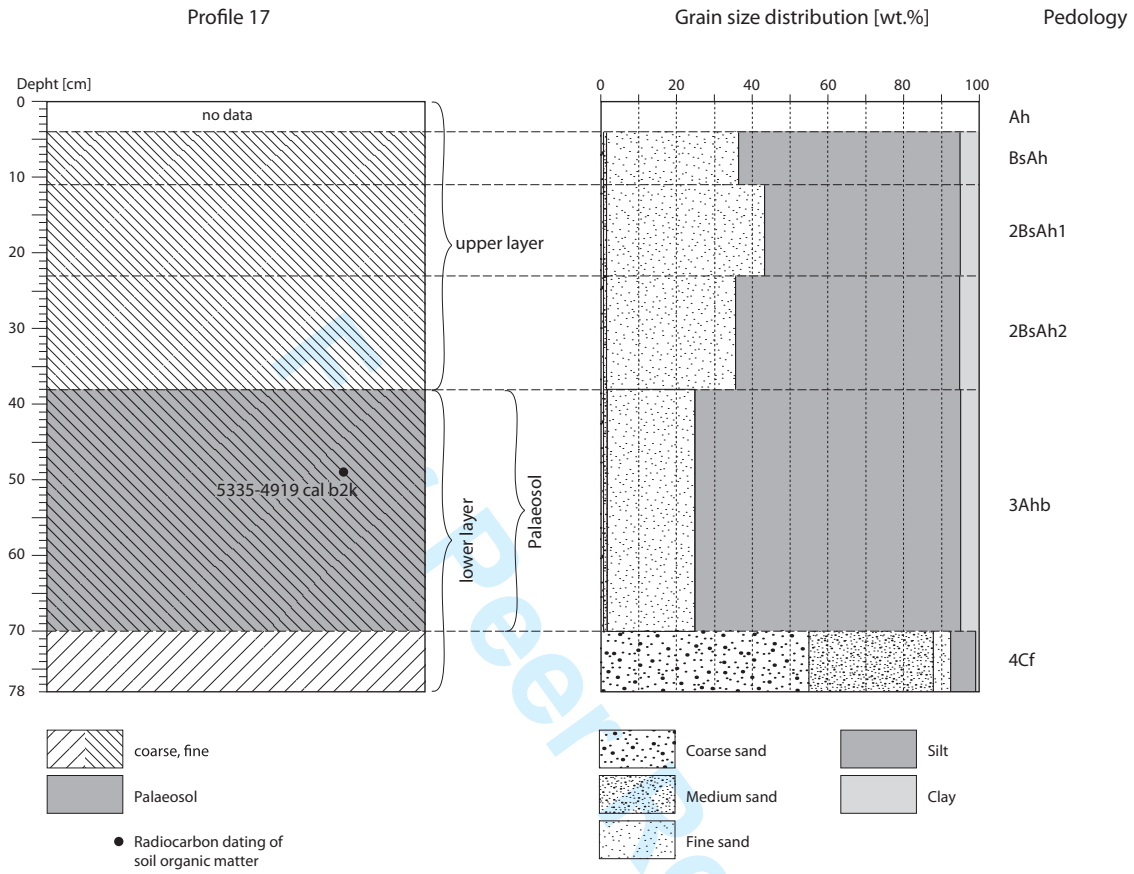
<sup>a</sup> Calibration was conducted using Oxcal version 4.2 (Bronk Ramsey, 2009)

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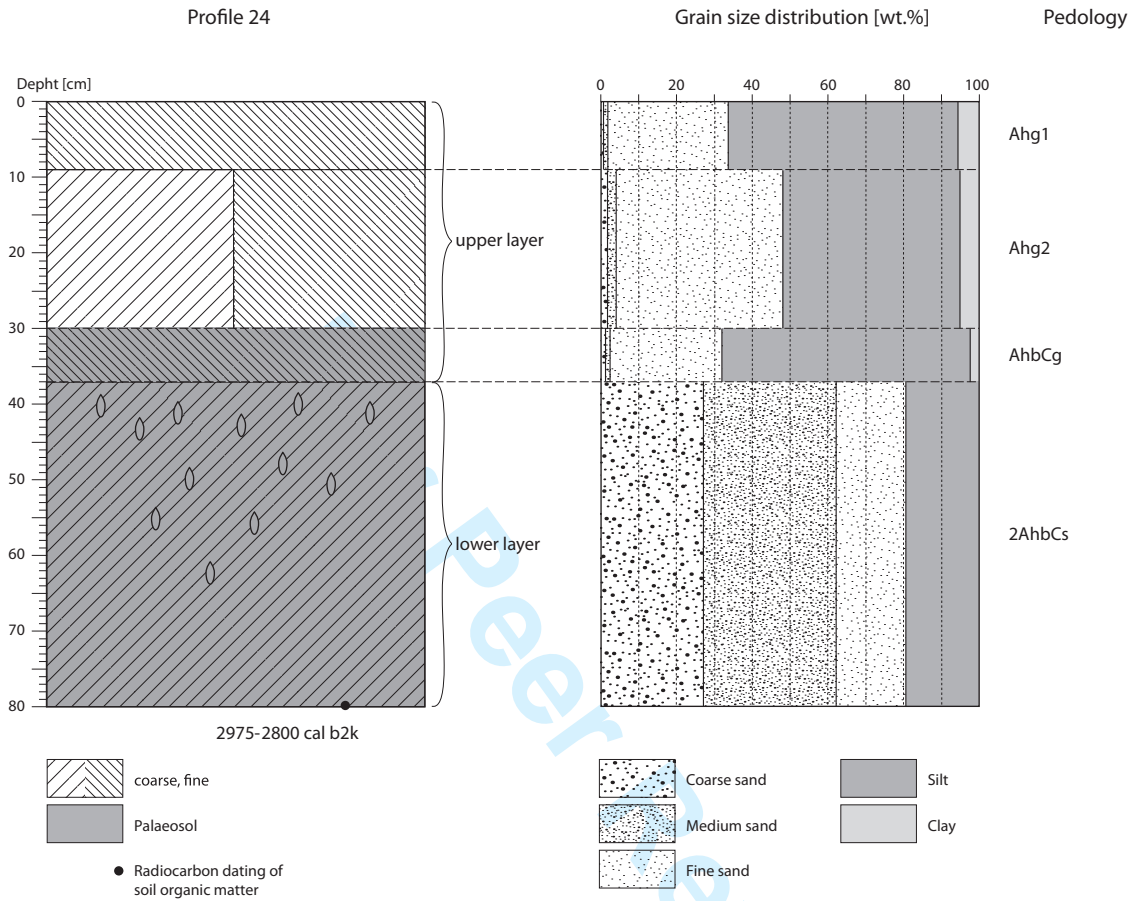
| Field ID | Laboratory ID | Sampling depth (cm) | <sup>226</sup> Ra ± s.e. (Bq/kg) | <sup>232</sup> Th ± s.e. (Bq/kg) | <sup>40</sup> K ± s.e. (Bq/kg) | Water content (%) | Total dose rate ± s.e. (Gy/ka) | n  | De ± s.e. (Gy) | g-value (%/decade) | age ± s.e. (ka) | Fading corrected age ± s.e. (ka) |
|----------|---------------|---------------------|----------------------------------|----------------------------------|--------------------------------|-------------------|--------------------------------|----|----------------|--------------------|-----------------|----------------------------------|
| D2 - 20  | 143078        | 20                  | 2.83 ± 0.27                      | 7.48 ± 0.33                      | 486 ± 10                       | 10.6              | 2.37 ± 0.08                    | 12 | 3.2 ± 0.2      | 3.81 ± 0.17        | 1.6 ± 0.1       | 2.2 ± 0.1                        |
| D2 - 53  | 143079        | 53                  | 3.49 ± 0.25                      | 7.73 ± 0.26                      | 453 ± 8                        | 7.5               | 2.33 ± 0.08                    | 12 | 12.8 ± 0.8     | 3.13 ± 0.20        | 5.5 ± 0.4       | 7.3 ± 0.6                        |
| D2 - 69  | 143080        | 69                  | 6.62 ± 0.31                      | 11.30 ± 0.39                     | 453 ± 9                        | 23.9              | 2.17 ± 0.07                    | 12 | 2.4 ± 0.1      | 2.87 ± 0.03        | 1.1 ± 0.1       | 1.4 ± 0.1                        |
| D2 - 115 | 143081        | 115                 | 7.62 ± 0.47                      | 11.60 ± 0.56                     | 404 ± 11                       | 22.9              | 2.04 ± 0.07                    | 12 | 5.7 ± 0.1      | 3.33 ± 0.12        | 2.8 ± 0.1       | 3.7 ± 0.2                        |

For Peer Review

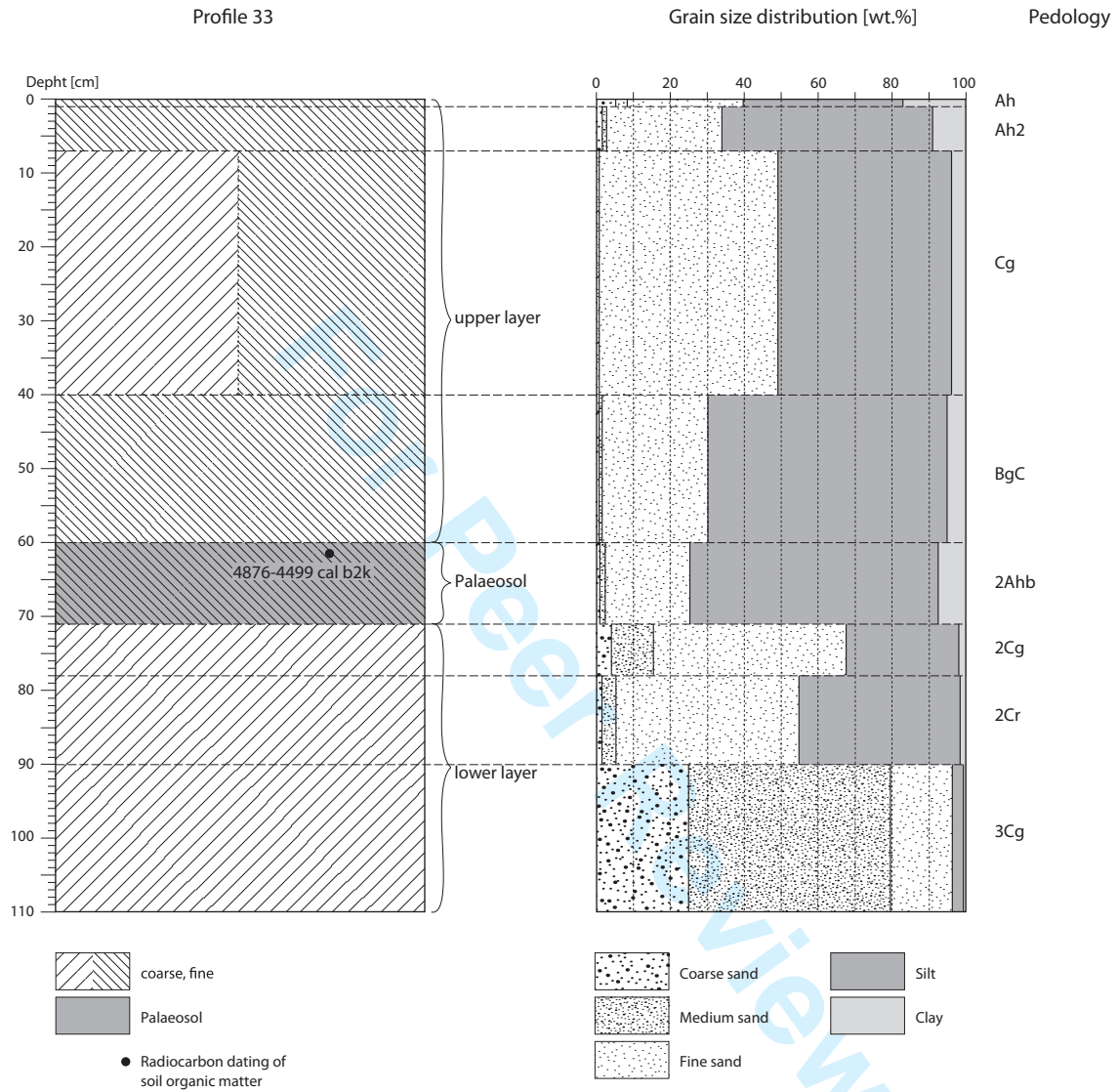
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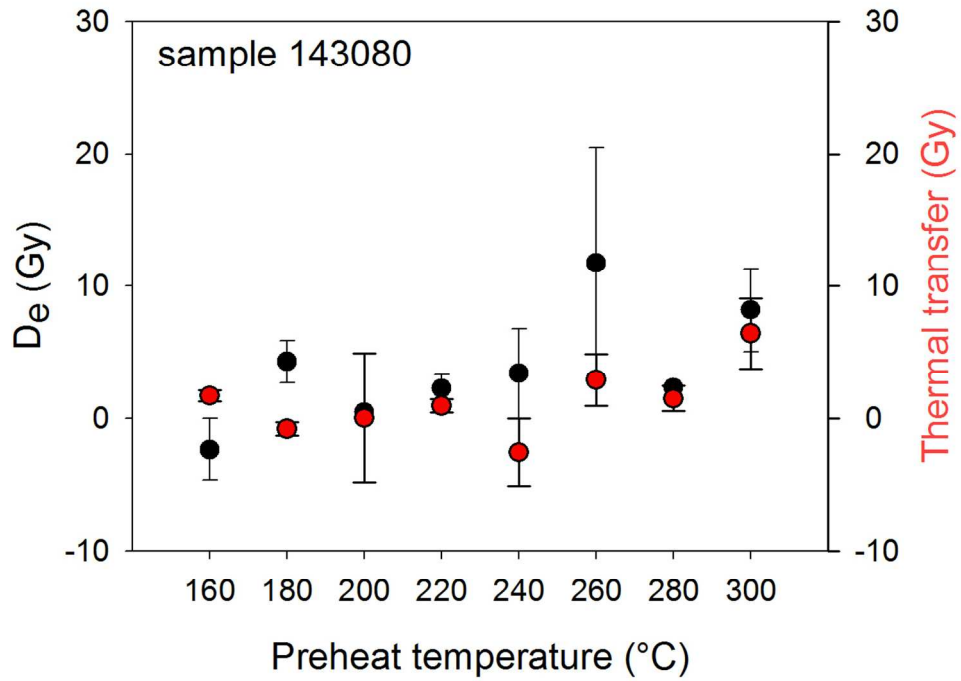
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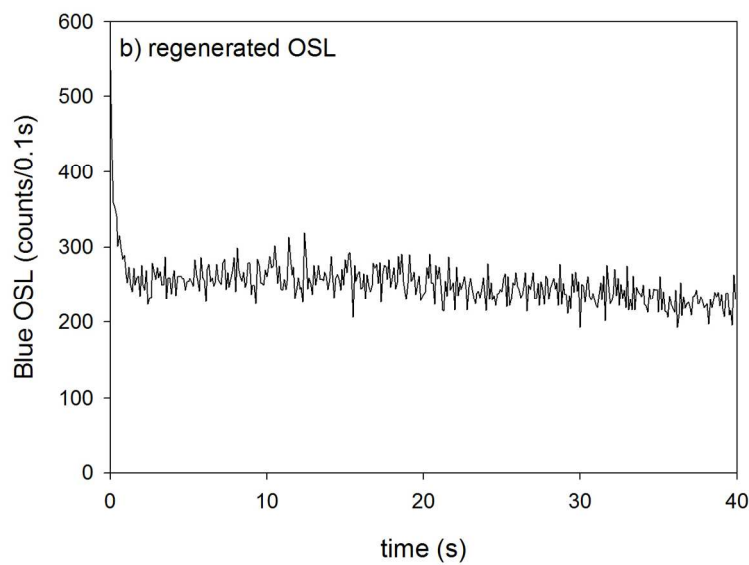
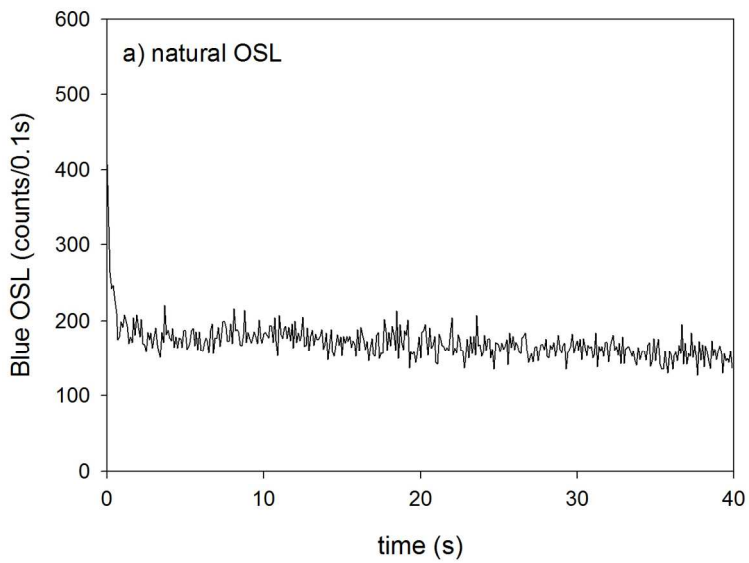






114x82mm (300 x 300 DPI)

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121x181mm (300 x 300 DPI)

| Profile | Horizon | Depth [cm] | cS   | mS   | fS   | ffS  | Sand    |      |      |     | Silt | Clay |
|---------|---------|------------|------|------|------|------|---------|------|------|-----|------|------|
|         |         |            |      |      |      |      | Sum     | cU   | mU   | fU  | Sum  | Sum  |
| 10-1    | OiOe    | -3         | 1.3  | 1.3  | 2.2  | 29.1 | 34      | 55.8 | 6.5  | 0.9 | 63   | 2.8  |
| 10-2    | Ah      | -9         | 0.3  | 1.0  | 2.0  | 30.3 | 34      | 54.6 | 8.0  | 1.4 | 64   | 2.5  |
| 10-3    | 2Ah     | -12        | 0.5  | 1.1  | 2.2  | 32.4 | 36      | 52.7 | 6.3  | 1.2 | 60   | 3.6  |
| 10-4    | 2C/Ahb  | -38        | 0.4  | 0.9  | 2.9  | 36.5 | 41      | 47.4 | 8.6  | 1.1 | 57   | 2.2  |
| 10-5    | 2Bhs    | 38-55+     | 1.7  | 2.5  | 2.2  | 22.4 | 29      | 53.3 | 13.7 | 1.0 | 68   | 3.2  |
| 11-1    | CfAh1   | -50        | 0.2  | 1.2  | 6.1  | 50.1 | 58      | 34.6 | 2.7  | 0.6 | 38   | 4.5  |
| 11-2    | CfAh2   | -75        |      |      |      |      | No data |      |      |     |      |      |
| 11-3    | CfAh3   | -100       |      |      |      |      | No data |      |      |     |      |      |
| 11-4    | CfAh4   | -125       |      |      |      |      | No data |      |      |     |      |      |
| 12-1    | Ah      | -3         | 0.9  | 1.3  | 3.6  | 34.6 | 40      | 45.9 | 8.3  | 0.8 | 55   | 4.7  |
| 12-2    | CAh     | -22        | 0.8  | 2.0  | 4.3  | 35.2 | 42      | 42.6 | 6.7  | 1.8 | 51   | 6.6  |
| 12-3    | Cfh     | 22+        | 0.6  | 1.4  | 6.2  | 44.3 | 53      | 38.0 | 4.4  | 0.5 | 43   | 4.5  |
| 13-1    | Ah      | -6         | 1.3  | 2.1  | 3.4  | 34.2 | 41      | 43.2 | 8.0  | 1.4 | 53   | 6.4  |
| 13-2    | CAh1    | -27        | 0.2  | 0.6  | 5.0  | 46.5 | 52      | 38.2 | 5.0  | 0.3 | 43   | 4.3  |
| 13-3    | CAh2    | -49        | 0.7  | 1.1  | 3.1  | 36.7 | 42      | 44.8 | 7.0  | 0.0 | 52   | 6.5  |
| 13-4    | C       | -60        | 2.7  | 4.4  | 3.4  | 27.0 | 37      | 46.9 | 10.7 | 0.3 | 58   | 4.6  |
| 13-5    | Ah      | -80        | 1.4  | 2.8  | 2.9  | 24.4 | 32      | 45.7 | 12.4 | 2.5 | 61   | 7.8  |
| 13-6    | C       | -90        | 12.3 | 13.1 | 5.2  | 17.4 | 48      | 36.2 | 10.6 | 0.7 | 48   | 4.4  |
| 13-7    | Ah      | -95        | 6.8  | 9.6  | 4.5  | 16.6 | 38      | 40.8 | 13.7 | 2.7 | 57   | 5.2  |
| 13-8    | C       | 95-117+    | 10.1 | 16.6 | 6.9  | 16.4 | 50      | 33.7 | 10.8 | 1.5 | 46   | 4.0  |
| 14-1    | Ah      | -2         | 0.4  | 0.8  | 2.5  | 35.6 | 39      | 49.5 | 6.1  | 1.3 | 57   | 3.7  |
| 14-2    | AhC     | -27        | 0.0  | 1.1  | 4.7  | 42.4 | 48      | 41.9 | 6.3  | 0.5 | 49   | 2.8  |
| 14-3    | 2CAhb   | -31        | 12.8 | 17.0 | 8.0  | 20.6 | 58      | 29.0 | 7.8  | 1.7 | 39   | 3.1  |
| 14-4    | 2C      | 31-45+     | 10.0 | 25.6 | 14.4 | 18.7 | 69      | 17.2 | 7.6  | 2.5 | 27   | 4.0  |
| 15-1    | CAh     | -18        | 1.1  | 0.6  | 5.3  | 44.3 | 51      | 39.5 | 7.5  | 0.5 | 47   | 1.3  |
| 15-2    | AhbC    | -40        | 0.1  | 0.3  | 3.5  | 37.3 | 41      | 45.2 | 4.3  | 1.3 | 51   | 7.9  |
| 15-3    | 2Ahb    | -45        | 0.2  | 0.4  | 4.1  | 41.8 | 46      | 37.6 | 6.4  | 1.5 | 46   | 8.1  |
| 15-4    | 2AhbC   | -65        | 0.0  | 0.4  | 2.3  | 35.1 | 38      | 49.7 | 3.5  | 0.7 | 54   | 8.3  |
| 15-5    | 3Ahb    | -67        |      |      |      |      | No data |      |      |     |      |      |

|      |        |         |      |      |      |      |         |      |      |     |    |      |
|------|--------|---------|------|------|------|------|---------|------|------|-----|----|------|
| 15-6 | 3Bgb   | -74     | 1.2  | 2.7  | 2.5  | 23.0 | 29      | 50.0 | 14.9 | 1.6 | 67 | 4.1  |
| 16-1 | Ah     | -12     | 0.3  | 1.1  | 2.8  | 35.2 | 39      | 48.0 | 7.2  | 1.3 | 57 | 4.0  |
| 16-2 | CAh    | -22     | 0.1  | 0.7  | 3.0  | 37.4 | 41      | 46.3 | 7.7  | 1.0 | 55 | 3.7  |
| 16-3 | 2CAhb  | -38     | 0.0  | 0.3  | 4.7  | 46.5 | 52      | 38.6 | 6.5  | 1.2 | 46 | 2.2  |
| 16-4 | 3C     | 38+     | 0.1  | 0.2  | 2.8  | 38.5 | 42      | 46.8 | 7.9  | 1.1 | 56 | 2.6  |
| 17-1 | Ah     | -4      |      |      |      |      | No data |      |      |     |    |      |
| 17-2 | BsAh   | -11     | 0.2  | 0.3  | 2.7  | 33.1 | 36      | 49.4 | 7.8  | 1.0 | 58 | 5.5  |
| 17-3 | 2BsAh1 | -23     | 0.1  | 0.4  | 3.7  | 39.2 | 43      | 43.6 | 7.1  | 0.7 | 51 | 5.2  |
| 17-4 | 2BsAh2 | -38     | 0.2  | 0.2  | 2.0  | 33.4 | 36      | 48.4 | 8.7  | 1.2 | 58 | 5.9  |
| 17-5 | 3Ahb   | -70     | 0.1  | 0.6  | 2.0  | 22.2 | 25      | 50.5 | 16.0 | 3.5 | 70 | 5.2  |
| 17-6 | 4Cf    | -78+ PF | 55.0 | 33.7 | 1.8  | 1.8  | 92      | 3.3  | 1.7  | 1.9 | 7  | 0.7  |
| 18-1 | CAh    | -7      |      |      |      |      | No data |      |      |     |    |      |
| 18-2 | Ahb    | -22     | 0.1  | 0.5  | 3.6  | 37.4 | 42      | 45.1 | 7.7  | 2.0 | 55 | 3.6  |
| 18-3 | 2CAhb  | -28     | 0.1  | 0.5  | 4.7  | 44.4 | 50      | 39.6 | 5.8  | 1.4 | 47 | 3.5  |
| 18-4 | 3Ahb   | 28-40+  | 0.2  | 0.4  | 4.2  | 40.4 | 45      | 42.7 | 6.8  | 1.0 | 51 | 4.2  |
| 19-1 | Ah     | -2      | 7.4  | 10.0 | 4.8  | 17.5 | 40      | 42.0 | 14.9 | 2.6 | 59 | 0.8  |
| 19-2 | AC     | -36     | 24.8 | 26.6 | 9.6  | 15.5 | 76      | 17.2 | 4.4  | 0.8 | 22 | 1.2  |
| 19-3 | 2C     | 36-40+  | 19.9 | 49.9 | 12.0 | 8.8  | 91      | 4.6  | 3.1  | 0.5 | 8  | 1.2  |
| 20-1 | Ah     | -6      | 0.5  | 2.0  | 4.0  | 38.9 | 45      | 46.0 | 5.0  | 0.8 | 52 | 2.8  |
| 20-2 | AhC    | -21     | 0.4  | 1.0  | 5.6  | 42.8 | 50      | 41.1 | 6.8  | 1.5 | 49 | 0.8  |
| 20-3 | CAh    | -36     | 0.8  | 2.6  | 3.4  | 32.0 | 39      | 49.1 | 9.7  | 1.2 | 60 | 1.2  |
| 20-4 | C      | -42     | 1.6  | 4.9  | 5.1  | 27.4 | 39      | 46.3 | 10.9 | 1.4 | 59 | 2.4  |
| 21-1 | Oi     | -6      |      |      |      |      | No data |      |      |     |    |      |
| 21-2 | AhC    | -32     | 0.2  | 0.9  | 3.9  | 34.7 | 40      | 44.2 | 8.9  | 2.5 | 56 | 4.8  |
| 21-3 | Ahb    | -40     | 0.4  | 3.1  | 3.3  | 29.1 | 36      | 45.4 | 9.2  | 1.8 | 56 | 7.8  |
| 22-1 | Ah     | -3      | 0.3  | 0.6  | 2.2  | 33.2 | 36      | 46.3 | 6.9  | 2.6 | 56 | 7.9  |
| 22-2 | CrAh   | -22     | 1.0  | 1.2  | 6.7  | 43.4 | 52      | 35.5 | 5.1  | 1.5 | 42 | 5.8  |
| 22-3 | AhCr   | -47     | 0.1  | 0.3  | 1.9  | 29.8 | 32      | 50.8 | 8.9  | 2.8 | 63 | 5.4  |
| 22-4 | 2Oe    | -61     | 0.3  | 1.0  | 1.9  | 22.0 | 25      | 47.7 | 10.7 | 4.3 | 63 | 12.2 |
| 22-5 | 2Oi    | -70     |      |      |      |      | No data |      |      |     |    |      |
| 22-6 | 3C     | -82+    | 5.9  | 28.6 | 21.3 | 24.2 | 80      | 14.7 | 2.7  | 1.1 | 18 | 1.6  |

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| 3  |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 4  |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 5  | 23-1 | Ah     | -2    | 0.3  | 2.5  | 3.1  | 30.8 | 37 | 47.3 | 7.4  | 1.8 | 56 | 6.9 |
| 6  | 23-2 | AhgC   | -28   | 0.1  | 0.5  | 3.5  | 38.7 | 43 | 45.0 | 7.2  | 0.8 | 53 | 4.2 |
| 7  | 23-3 | Bs     | -33   | 9.9  | 21.5 | 11.0 | 17.4 | 60 | 24.2 | 10.3 | 2.3 | 37 | 3.5 |
| 8  | 23-4 | 2Cg    | -41   | 13.7 | 25.2 | 11.9 | 15.1 | 66 | 18.6 | 9.9  | 1.9 | 30 | 3.6 |
| 9  | 23-5 | 3C     | -44   | 12.0 | 16.1 | 11.8 | 20.0 | 60 | 24.8 | 10.6 | 2.0 | 37 | 2.7 |
| 10 | 23-6 | 4C     | -59   | 1.4  | 10.7 | 14.5 | 31.7 | 58 | 30.6 | 6.8  | 0.4 | 38 | 3.9 |
| 11 | 23-7 | 5Cd    | -78+  | 22.4 | 48.9 | 13.0 | 8.7  | 93 | 3.8  | 1.0  | 0.1 | 5  | 2.1 |
| 12 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 13 | 24-1 | Ahg1   | -9    | 0.3  | 0.7  | 2.7  | 30.1 | 34 | 50.8 | 7.6  | 1.7 | 60 | 6.2 |
| 14 | 24-2 | Ahg2   | -30   | 1.5  | 2.3  | 4.4  | 39.8 | 48 | 38.3 | 5.5  | 2.8 | 47 | 5.4 |
| 15 | 24-3 | AhbCg  | -37   | 1.1  | 1.2  | 1.8  | 27.4 | 31 | 53.5 | 11.3 | 1.3 | 66 | 2.5 |
| 16 | 24-4 | 2AhbCs | -70+  | 26.8 | 35.5 | 8.4  | 9.7  | 80 | 12.9 | 5.2  | 1.5 | 20 | 0.0 |
| 17 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 18 | 25-1 | Ah     | -4    | 0.2  | 0.3  | 1.8  | 31.6 | 34 | 55.0 | 6.5  | 1.3 | 63 | 3.4 |
| 19 | 25-2 | CAh    | -10   | 0.0  | 0.3  | 3.3  | 37.3 | 41 | 46.3 | 9.2  | 1.7 | 57 | 2.0 |
| 20 | 25-3 | 2C1    | -21   | 0.6  | 0.6  | 1.7  | 26.8 | 30 | 57.3 | 10.1 | 1.9 | 69 | 0.9 |
| 21 | 25-4 | 2C2    | -34   | 3.3  | 3.7  | 2.2  | 17.6 | 27 | 54.3 | 15.9 | 1.7 | 72 | 1.2 |
| 22 | 25-5 | 3C     | -49+  | 24.9 | 28.0 | 10.5 | 10.9 | 74 | 16.4 | 6.9  | 1.3 | 25 | 1.1 |
| 23 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 24 | 26-1 | Ah     | -23   | 0.0  | 0.4  | 3.6  | 37.9 | 42 | 43.7 | 7.1  | 2.6 | 53 | 4.6 |
| 25 | 26-2 | AhC    | -40   | 0.0  | 0.2  | 2.2  | 35.9 | 38 | 49.7 | 6.7  | 1.2 | 58 | 4.1 |
| 26 | 26-3 | C      | -50   | 0.1  | 0.4  | 2.0  | 29.0 | 32 | 53.3 | 12.2 | 1.5 | 67 | 1.5 |
| 27 | 26-4 | 2C     | -100+ | 17.5 | 21.9 | 5.5  | 11.2 | 56 | 30.5 | 11.2 | 1.0 | 43 | 1.3 |
| 28 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 29 | 27-1 | AhC1   | -3    | 1.6  | 3.1  | 5.2  | 36.6 | 47 | 41.9 | 7.3  | 1.1 | 50 | 3.2 |
| 30 | 27-2 | AhC2   | -8    | 0.1  | 1.0  | 4.0  | 32.1 | 37 | 46.5 | 10.2 | 1.1 | 58 | 4.9 |
| 31 | 27-3 | 2Ahb   | -12   | 0.1  | 0.6  | 4.5  | 45.5 | 51 | 39.3 | 6.3  | 0.4 | 46 | 3.2 |
| 32 | 27-4 | 3AhC1  | -27   | 0.0  | 0.3  | 2.4  | 32.2 | 35 | 52.6 | 8.8  | 0.9 | 62 | 2.8 |
| 33 | 27-5 | 3AhC2  | -40   | 0.9  | 3.6  | 3.3  | 23.6 | 31 | 50.4 | 13.8 | 1.3 | 65 | 3.0 |
| 34 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 35 | 28-1 | Ah     | -1    | 12.6 | 5.9  | 3.3  | 23.9 | 46 | 39.5 | 11.8 | 1.2 | 52 | 1.9 |
| 36 | 28-2 | C      | -18   | 9.4  | 9.1  | 3.9  | 16.0 | 39 | 42.6 | 15.5 | 1.9 | 60 | 1.5 |
| 37 | 28-3 | 2C     | -78+  | 13.4 | 27.5 | 13.9 | 17.3 | 72 | 14.7 | 8.0  | 3.0 | 26 | 2.1 |
| 38 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 39 | 30-1 | Ah     | -7    | 0.7  | 1.7  | 4.2  | 39.7 | 46 | 42.3 | 6.1  | 1.0 | 49 | 4.3 |
| 40 | 30-2 | CAh1   | -15   | 0.0  | 0.4  | 3.7  | 36.6 | 41 | 46.5 | 9.0  | 1.7 | 57 | 2.0 |
| 41 | 30-3 | CAh2   | -41   | 0.1  | 0.4  | 3.0  | 38.7 | 42 | 46.7 | 8.3  | 0.8 | 56 | 1.9 |
| 42 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 43 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 44 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 45 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 46 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 47 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 48 |      |        |       |      |      |      |      |    |      |      |     |    |     |
| 49 |      |        |       |      |      |      |      |    |      |      |     |    |     |

|      |       |      |      |      |      |      |         |      |      |     |    |      |
|------|-------|------|------|------|------|------|---------|------|------|-----|----|------|
| 30-4 | 2C    | -63  | 30.3 | 33.5 | 12.8 | 11.6 | 88      | 6.6  | 3.3  | 0.6 | 11 | 1.3  |
| 30-5 | 3C    | -83  | 15.2 | 30.1 | 13.0 | 16.0 | 74      | 15.0 | 7.4  | 1.9 | 24 | 1.4  |
| 31-1 | Ah    | -4   | 1.4  | 2.3  | 3.4  | 34.5 | 42      | 44.6 | 6.7  | 1.4 | 53 | 5.6  |
| 31-2 | CAh   | -13  | 0.5  | 2.0  | 5.5  | 37.9 | 46      | 41.5 | 10.0 | 1.3 | 53 | 1.3  |
| 31-3 | 2CAh1 | -40  | 0.3  | 0.5  | 5.7  | 43.9 | 50      | 37.2 | 5.9  | 0.3 | 44 | 6.1  |
| 31-4 | 2CAh2 | -75  | 0.9  | 1.0  | 2.0  | 31.1 | 35      | 48.9 | 8.0  | 0.5 | 57 | 7.6  |
| 32-1 | Ah    | -4   |      |      |      |      | No data |      |      |     |    |      |
| 32-2 | C1    | -12  | 0.0  | 0.3  | 4.5  | 38.3 | 43      | 47.8 | 5.7  | 0.7 | 54 | 2.7  |
| 32-3 | C2    | -39  | 0.9  | 1.3  | 2.3  | 31.3 | 36      | 50.3 | 10.2 | 1.1 | 62 | 2.5  |
| 32-4 | 2C    | -115 | 9.0  | 27.0 | 15.5 | 20.1 | 72      | 16.5 | 5.9  | 2.4 | 25 | 3.7  |
| 33-1 | Ah    | -1   | 5.9  | 2.1  | 2.8  | 28.8 | 40      | 30.7 | 9.6  | 3.0 | 43 | 17.0 |
| 33-2 | Ah2   | -7   | 1.7  | 1.3  | 2.1  | 28.4 | 33      | 49.3 | 6.5  | 1.8 | 58 | 8.9  |
| 33-3 | Cg    | -40  | 0.0  | 0.3  | 4.4  | 44.5 | 49      | 40.3 | 5.4  | 1.3 | 47 | 3.6  |
| 33-4 | BgC   | -60  | 0.3  | 0.7  | 2.4  | 26.8 | 30      | 51.6 | 10.5 | 2.4 | 65 | 5.2  |
| 33-5 | 2Ahb  | -71  | 0.5  | 1.3  | 2.3  | 22.0 | 26      | 47.8 | 14.3 | 4.2 | 66 | 7.6  |
| 33-6 | 2Cg   | -78  | 3.9  | 11.9 | 16.8 | 34.4 | 67      | 24.0 | 5.4  | 1.8 | 31 | 1.8  |
| 33-7 | 2Cr   | -90  | 1.2  | 4.1  | 9.3  | 39.6 | 54      | 34.4 | 8.2  | 1.8 | 44 | 1.4  |
| 33-8 | 3Cg   | -110 | 24.2 | 54.9 | 11.3 | 6.1  | 96      | 2.4  | 0.4  | 0.1 | 3  | 0.7  |
| 34-1 | Ah    | -4   | 0.2  | 0.9  | 2.2  | 36.5 | 40      | 47.5 | 6.8  | 1.7 | 56 | 4.2  |
| 34-2 | CAh   | -26  | 0.2  | 1.2  | 4.2  | 40.8 | 46      | 43.6 | 6.2  | 0.7 | 51 | 3.0  |
| 34-3 | C     | -45+ | 1.3  | 1.8  | 2.2  | 23.7 | 29      | 53.5 | 13.8 | 1.9 | 69 | 1.8  |
| 35-1 | Ah    | -5   | 0.6  | 2.0  | 4.1  | 32.4 | 39      | 42.0 | 9.3  | 3.0 | 54 | 6.5  |
| 35-2 | Bg    | -43  | 0.7  | 4.2  | 10.4 | 45.6 | 61      | 33.5 | 3.8  | 0.6 | 38 | 1.3  |
| 35-3 | Wr11  | -52  | 0.7  | 4.1  | 12.2 | 34.8 | 52      | 38.4 | 6.9  | 1.3 | 47 | 1.6  |
| 35-4 | Wr12  | -52+ | 0.1  | 12.5 | 39.6 | 37.8 | 90      | 8.4  | 0.4  | 0.3 | 9  | 0.7  |
| 36-1 | Ah    | -9   | 2.7  | 11.2 | 7.7  | 29.3 | 51      | 35.3 | 5.4  | 1.8 | 42 | 6.6  |
| 36-2 | CAh   | -48  | 2.0  | 4.0  | 8.1  | 37.7 | 52      | 38.1 | 3.6  | 1.1 | 43 | 5.3  |
| 36-3 | 2CAh  | -94  | 0.3  | 1.3  | 4.1  | 42.4 | 48      | 42.1 | 5.7  | 0.0 | 48 | 4.1  |
| 37-1 | Ah    | -8   | 0.3  | 1.5  | 3.9  | 37.2 | 43      | 40.1 | 7.8  | 1.7 | 50 | 7.6  |
| 37-2 | CAh1  | -47  | 0.1  | 0.5  | 3.5  | 39.6 | 44      | 41.6 | 6.5  | 1.5 | 50 | 6.7  |
| 37-3 | CAh2  | -61  | 0.0  | 0.3  | 2.1  | 32.5 | 35      | 50.3 | 5.4  | 3.5 | 59 | 5.9  |

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|----|------|-------|-------|------|------|------|------|----|------|------|-----|----|-----|
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| 2  |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 3  |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 4  |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 5  | 37-4 | 2CAhb |       | 0.0  | 0.2  | 1.5  | 31.1 | 33 | 52.2 | 7.9  | 2.2 | 62 | 5.0 |
| 6  | 38-1 | Ah    | -5    | 0.0  | 0.2  | 1.2  | 26.8 | 28 | 56.9 | 8.4  | 1.5 | 67 | 5.0 |
| 7  | 38-2 | CAh1  | -16   | 0.1  | 0.2  | 3.5  | 37.2 | 41 | 46.6 | 9.0  | 1.4 | 57 | 2.0 |
| 8  | 38-3 | CAh2  | -30   | 0.0  | 0.1  | 2.3  | 37.5 | 40 | 48.4 | 9.1  | 0.8 | 58 | 1.7 |
| 9  | 38-4 | 2C    | -46   | 0.2  | 0.6  | 1.6  | 20.2 | 23 | 58.7 | 15.4 | 2.0 | 76 | 1.3 |
| 10 | 38-5 | 3C1   | -71   | 9.1  | 25.3 | 12.8 | 17.1 | 64 | 19.7 | 11.5 | 3.9 | 35 | 0.6 |
| 11 | 38-6 | 3C2   | -71+  | 15.3 | 26.5 | 14.0 | 17.1 | 73 | 15.5 | 7.8  | 3.1 | 26 | 0.6 |
| 12 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 13 | 39-1 | Ah    | -6    | 3.7  | 4.8  | 4.5  | 36.5 | 49 | 39.7 | 6.1  | 1.3 | 47 | 3.5 |
| 14 | 39-2 | CAh   | -35   | 0.9  | 1.6  | 4.6  | 44.0 | 51 | 39.9 | 6.1  | 0.5 | 46 | 2.4 |
| 15 | 39-3 | 2Ahb  | -58   | 0.9  | 1.3  | 2.1  | 30.4 | 35 | 52.5 | 9.1  | 2.0 | 64 | 1.8 |
| 16 | 39-4 | 3C    | -79   | 14.8 | 25.7 | 12.5 | 15.7 | 69 | 18.8 | 7.6  | 2.8 | 29 | 2.2 |
| 17 | 39-5 | 4C    | -79+  | 15.3 | 26.7 | 12.6 | 16.0 | 71 | 15.0 | 8.7  | 3.5 | 27 | 2.2 |
| 18 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 19 | 40-1 | AhC   | -10   | 1.0  | 1.5  | 3.2  | 35.3 | 41 | 45.4 | 8.6  | 1.0 | 55 | 4.0 |
| 20 | 40-2 | CAhg  | -20   | 0.9  | 1.4  | 5.0  | 43.2 | 51 | 39.6 | 5.2  | 0.6 | 45 | 4.1 |
| 21 | 40-3 | CAhgb | -37   | 0.7  | 1.2  | 5.2  | 48.3 | 55 | 32.4 | 4.7  | 2.5 | 40 | 5.0 |
| 22 | 40-4 | Oeg   | -43   | 0.5  | 1.1  | 5.6  | 48.1 | 55 | 31.7 | 3.3  | 2.0 | 37 | 7.6 |
| 23 | 40-5 | Arhf  | -50   | 0.5  | 1.8  | 5.2  | 47.2 | 55 | 36.2 | 3.6  | 0.9 | 41 | 4.5 |
| 24 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 25 | 41-1 | OaAh  | -14   | 2.9  | 2.5  | 3.4  | 30.9 | 40 | 49.4 | 4.0  | 0.5 | 54 | 6.5 |
| 26 | 41-2 | Ah    | -20   | 0.4  | 1.0  | 3.8  | 34.9 | 40 | 45.3 | 8.3  | 2.0 | 56 | 4.4 |
| 27 | 41-3 | Oef   | -20+  | 0.2  | 1.1  | 4.3  | 37.2 | 43 | 42.5 | 6.3  | 1.9 | 51 | 6.6 |
| 28 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 29 | 42-1 | Ah    | -4    | 0.4  | 1.5  | 3.1  | 34.7 | 40 | 43.0 | 7.9  | 2.2 | 53 | 7.2 |
| 30 | 42-2 | AhC   | -23   | 0.1  | 0.4  | 3.4  | 37.7 | 42 | 46.4 | 7.1  | 1.8 | 55 | 3.2 |
| 31 | 42-3 | 2Ch   | -39   | 4.9  | 8.2  | 4.2  | 22.5 | 40 | 42.2 | 12.9 | 2.6 | 58 | 2.4 |
| 32 | 42-4 | 3CAhb | -50   | 1.5  | 2.3  | 2.6  | 31.8 | 38 | 46.1 | 10.4 | 1.7 | 58 | 3.6 |
| 33 | 42-5 | 4C    | -52   | 5.3  | 7.2  | 4.3  | 23.2 | 40 | 42.5 | 12.7 | 2.1 | 57 | 2.7 |
| 34 | 42-6 | 5C    | -54   | 8.0  | 11.7 | 5.4  | 19.9 | 45 | 39.4 | 11.2 | 2.7 | 53 | 1.7 |
| 35 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 36 | 43-1 | Ah    | -10   | 2.1  | 3.0  | 6.8  | 34.4 | 46 | 41.4 | 7.0  | 1.3 | 50 | 3.9 |
| 37 | 43-2 | 2Cg   | -13   | 4.1  | 23.2 | 16.4 | 29.4 | 73 | 22.2 | 3.3  | 1.2 | 27 | 0.1 |
| 38 | 43-3 | 2AhgC | 18-27 | 0.0  | 0.4  | 3.2  | 22.7 | 26 | 37.1 | 21.1 | 8.8 | 67 | 6.7 |
| 39 | 43-4 | 3Ahgb | 54-77 | 1.7  | 5.1  | 4.9  | 21.2 | 33 | 48.1 | 13.2 | 2.6 | 64 | 3.3 |
| 40 | 44-1 | CAh   | -26   | 3.4  | 7.8  | 8.5  | 57.0 | 77 | 20.5 | 1.2  | 0.8 | 23 | 0.8 |
| 41 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 42 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 43 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 44 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 45 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 46 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 47 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 48 |      |       |       |      |      |      |      |    |      |      |     |    |     |
| 49 |      |       |       |      |      |      |      |    |      |      |     |    |     |

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|------|--------|-------|------|------|------|------|----|------|------|-----|----|-----|
| 44-2 | AhbC   | -31   | 0.2  | 1.2  | 4.3  | 38.2 | 44 | 45.8 | 8.3  | 0.5 | 55 | 1.4 |
| 44-3 | CAhb   | -45   | 0.5  | 2.4  | 5.9  | 44.6 | 53 | 39.3 | 5.2  | 0.3 | 45 | 1.7 |
| 44-4 | AhbC   | -76   | 0.0  | 0.6  | 2.7  | 38.0 | 41 | 49.4 | 7.2  | 0.7 | 57 | 1.3 |
| 45-1 | Ah     | -6    | 1.1  | 12.5 | 10.3 | 30.5 | 54 | 34.2 | 4.9  | 1.2 | 40 | 5.3 |
| 45-2 | CAh    | -14   | 0.1  | 0.4  | 4.5  | 37.7 | 43 | 42.8 | 7.9  | 2.0 | 53 | 4.6 |
| 45-3 | 2AhbC  | -45   | 0.0  | 0.4  | 4.3  | 42.0 | 47 | 42.7 | 5.9  | 2.3 | 51 | 2.5 |
| 45-4 | 2C     | -70+  | 2.9  | 7.0  | 5.5  | 29.3 | 45 | 41.5 | 10.1 | 1.6 | 53 | 2.2 |
| 46-1 | Ah     | -12   | 0.5  | 4.8  | 3.9  | 34.3 | 44 | 44.6 | 8.3  | 1.7 | 55 | 1.8 |
| 46-2 | C      | -24   | 0.0  | 0.4  | 4.4  | 39.8 | 45 | 45.8 | 7.9  | 0.7 | 54 | 1.0 |
| 46-3 | AhbC   | -30   | 0.0  | 0.3  | 4.9  | 44.2 | 49 | 41.4 | 7.4  | 0.4 | 49 | 1.5 |
| 46-4 | C      | -52   | 1.7  | 5.8  | 3.0  | 31.7 | 42 | 47.1 | 10.0 | 0.0 | 57 | 0.8 |
| 46-5 | 2C     | -95   | 28.0 | 64.1 | 5.3  | 0.9  | 98 | 0.2  | 1.3  | 0.9 | 2  | 0.1 |
| 46-6 | 3C     | -100+ | 0.2  | 54.9 | 29.8 | 12.0 | 97 | 2.5  | 0.2  | 0.1 | 3  | 0.2 |
| 47-1 | AhC    | -10   | 0.3  | 14.7 | 16.1 | 38.9 | 70 | 26.5 | 1.6  | 0.3 | 28 | 2.1 |
| 47-2 | Ahb    | -20   | 0.1  | 0.7  | 2.4  | 30.7 | 34 | 49.5 | 9.1  | 1.8 | 60 | 5.6 |
| 47-3 | CAhb   | -70   | 0.1  | 0.7  | 2.3  | 30.5 | 34 | 53.8 | 8.5  | 1.4 | 64 | 2.8 |
| 47-4 | C      | -95+  | 0.1  | 0.2  | 2.4  | 31.3 | 34 | 52.9 | 9.0  | 1.3 | 63 | 2.9 |
| 48-1 | AhC1   | -15   | 0.0  | 0.4  | 3.5  | 37.7 | 42 | 44.9 | 8.8  | 1.1 | 55 | 3.6 |
| 48-2 | AhC2   | -30   | 0.0  | 0.3  | 3.7  | 38.4 | 42 | 46.1 | 8.3  | 1.0 | 55 | 2.2 |
| 48-3 | C1     | -45   | 2.5  | 0.1  | 1.5  | 31.2 | 35 | 53.9 | 9.2  | 1.5 | 65 | 0.1 |
| 48-4 | C2     | -65   | 0.5  | 1.0  | 2.1  | 21.6 | 25 | 57.0 | 14.6 | 2.2 | 74 | 1.0 |
| D0-a | C/dune | -20   | 16.3 | 35.5 | 18.8 | 17.0 | 88 | 9.0  | 1.4  | 0.5 | 11 | 1.6 |
| D0-b | C/dune | -44   | 4.1  | 23.3 | 20.8 | 33.3 | 81 | 15.1 | 1.0  | 0.1 | 16 | 2.5 |
| D0-c | C/dune | -47   | 16.9 | 46.8 | 8.8  | 13.4 | 86 | 9.3  | 2.0  | 0.7 | 12 | 2.2 |
| D0-d | 2Ahb1  | -57   | 17.2 | 20.8 | 6.0  | 27.1 | 71 | 22.4 | 2.9  | 1.0 | 26 | 2.7 |
| D0-e | 2Ahb2  | 58+   | 13.2 | 19.8 | 6.6  | 26.3 | 66 | 26.4 | 4.0  | 0.4 | 31 | 3.3 |
| D1-a | C/dune | -4    | 36.1 | 25.5 | 10.6 | 17.2 | 89 | 7.7  | 1.3  | 0.1 | 9  | 1.8 |
| D1-b | C/dune | -7    | 44.7 | 26.3 | 9.1  | 12.0 | 92 | 6.3  | 0.4  | 0.1 | 7  | 1.0 |
| D1-c | C/dune | -10   | 4.6  | 22.8 | 12.9 | 35.9 | 76 | 18.7 | 0.1  | 0.3 | 19 | 4.7 |
| D1-d | C/dune | 55-65 | 8.8  | 22.4 | 11.1 | 29.4 | 72 | 25.3 | 0.7  | 0.2 | 26 | 2.1 |
| D1-e | 2Ahb1  | 65-67 | 4.8  | 9.7  | 6.8  | 42.5 | 64 | 29.2 | 3.1  | 0.4 | 33 | 3.7 |



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|------|--------|-------|------|------|------|------|----|------|------|-----|----|-----|
| D1-f | 2Ahb2  | -98   | 0.6  | 3.1  | 9.7  | 45.8 | 59 | 35.0 | 2.9  | 0.2 | 38 | 2.6 |
| D1-g | 2Ahb3  | 99+   | 0.2  | 0.9  | 4.9  | 46.0 | 52 | 37.9 | 4.4  | 1.0 | 43 | 4.6 |
| D2-a | C/dune | -13   | 6.8  | 28.9 | 20.7 | 27.1 | 84 | 13.6 | 1.3  | 0.1 | 15 | 1.3 |
| D2-b | C/dune | -28   | 25.0 | 30.8 | 13.4 | 18.7 | 88 | 9.8  | 1.1  | 0.1 | 11 | 1.1 |
| D2-c | C/dune | 57-59 | 7.1  | 27.1 | 30.1 | 29.1 | 94 | 4.7  | 0.1  | 0.3 | 5  | 1.4 |
| D2-d | 2C     | 61-71 | 1.0  | 4.2  | 5.7  | 41.1 | 52 | 39.2 | 5.1  | 0.9 | 45 | 2.7 |
| D2-e | 3AhC   | -81   | 0.1  | 1.0  | 5.5  | 44.6 | 51 | 41.7 | 4.1  | 0.7 | 46 | 2.3 |
| D2-f | 4Ahb1  | -96   | 0.0  | 0.6  | 4.2  | 41.4 | 46 | 43.0 | 5.1  | 0.8 | 49 | 4.8 |
| D2-g | 4Ahb2  | -112  | 0.0  | 0.5  | 4.9  | 47.7 | 53 | 39.0 | 4.3  | 0.8 | 44 | 2.8 |
| D2-h | 4Ahb3  | 112+  | 0.0  | 0.4  | 1.5  | 31.1 | 33 | 56.1 | 5.7  | 2.0 | 64 | 3.1 |
| D3-a | C/dune | -12   | 23.3 | 41.6 | 11.3 | 12.0 | 88 | 9.9  | 0.7  | 0.4 | 11 | 0.9 |
| D3-b | 2C     | -17   | 0.9  | 2.2  | 3.9  | 34.5 | 41 | 46.6 | 8.0  | 0.8 | 55 | 3.1 |
| D3-c | 3AhC   | -22   | 0.1  | 0.6  | 4.3  | 40.6 | 45 | 42.9 | 7.3  | 0.7 | 51 | 3.7 |
| D3-d | 4Ahb1  | -32   | 0.5  | 0.9  | 4.9  | 42.4 | 49 | 40.0 | 7.5  | 0.8 | 48 | 3.0 |
| D3-e | 4Ahb2  | -35   | 0.0  | 0.2  | 3.2  | 43.6 | 47 | 45.3 | 6.5  | 0.8 | 53 | 0.3 |
| D3-f | 4Ahb3  | -39   | 2.2  | 3.3  | 2.9  | 26.4 | 35 | 50.8 | 11.8 | 1.5 | 64 | 1.1 |
| D3-g | 4Ahb4  | 40+   | 18.1 | 27.6 | 12.8 | 15.5 | 74 | 14.0 | 7.3  | 2.2 | 24 | 2.5 |

| No. | Site description                                 | Aspect | Inclination [°] | Width [m] | Length [m] | Depth [cm] |
|-----|--|--------|-----------------|-----------|------------|------------|
| 1   | Slope  | SE     | 13              | 18        | 10-14      | 65         |
| 2   | Crest, bowl-shaped                               | SE     | 9               | 1.80      | 3          | 45         |
| 3   | Upper slope range, strongly wind exposed         | E-SE   | 11              | 4         | 8          | 50         |
| 4   | Steep slope, strongly wind exposed               | S      | 11              | 2.50-25   | 3-10       | 70         |
| 5   | Steep slope, vegetated bowl, more wind protected | S      | 19              | 2.50      | 7.50       | 64         |
| 6   | Almost hilltop, partly vegetated                 | S      | 8               | 3.10      | 7.20       | 52         |
| 7   | Moraine  | S-SE   | 9               | 6         | 7          | 32         |
| 8   | Bouldery   | SE     | 9               | 36        | 24         | 50         |
| 9   | Moraine  | S-SE   | 8               | 27        | 23         | 35         |
| 10  | Moraine, aeolian blow-outs in luv and lee        | E-SE   | 7               | 7         | 6          | 43         |
| 11  | Moraine  | SE     | 12              | 20        | 200        | 40         |
| 12  | Moraine in dunefield, barren of vegetation       | SE     | 13              | 4         | 8.30       | 70         |
| 13  | Moraine in dunefield                             | S-SE   | 8               | 25        | 75         | 80         |
| 14  | Moraine in dunefield                             | S-SE   | 13              | 6.10      | 10.60      | 95         |
| 15  | Moraine in dunefield, bouldery                   | SE     | 1               | 25        | 190        | 60         |
| 16  | Moraine in dunefield                             | SE     | 7               | 8-15      | 20         | 55         |